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BULLETIN

OF THE

AMERICAN PHYSICAL SOCIETY

INCLUDING THE

PROGRAMME OF THE

1958 MARCH MEETING

AT

CHICAGO, ILLINOIS

MARCH 27–28–29, 1958

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Table of Contents

1958 March meeting at the University of Chicago:

Preamble 94

Epitome 97

Programme 98

Index 148

Reminder of 1958 Spring Meeting at Washington 151

Announcement of 1958 Summer Meeting at Ithaca 151

Officers of Divisions convening at this Meeting 151

Calendar of 1958 Meetings and Deadlines 152

Rules and instructions for the preparation of abstracts 152

Important notice about new Membership List. 152

Minutes of the 1957 Fall Meeting of the New England Section, October 19, 1957 153

Reservation form for Chicago Banquet 155

March 27, 1958 Series II, Vol. 3, No. 2

BULLETIN

OF THE

AMERICAN PHYSICAL SOCIETY

1958 March Meeting at Chicago, March 27–29, 1958

THE **American Physical Society** will hold its **1958 March meeting at Chicago,** in the buildings of the University of Chicago and under the particular auspices of the Institute for the Study of Metals of that University, on **Thursday, Friday, and Saturday, March 27, 28, and 29.** The "March meeting" was instituted by our Council several years ago to provide opportunity for the special programmes of the Divisions of the Society. It has more than justified itself. This Bulletin will show that three of our Divisions—in order of seniority, those of High-Polymer Physics (hereinafter denoted by DHPP), Solid-State Physics (DSSP), and Chemical Physics (DCP)—are convening at Chicago, and that the number of contributed papers has soared from the previous maximum 224 to a record 260. The Local Committee is headed by E. A. Long, to whom and to whose aides we shall be deeply indebted.

The **Hotel Windermere,** at 1642 East 56th Street, has assumed the responsibility of taking care of our members. Those who write early enough will be accommodated there: those who write to the Windermere after its accommodations are fully booked will be put up elsewhere in the region.

Though Chicago is the usual theater of our November meetings, there may be many at this convention who will be paying their first visit to the University of Chicago, and they may welcome some advice about geography. The University is about seven miles south of the "Loop" or downtown business district of Chicago. There are no hotels within half a mile of the University; the nearest group of hotels, of which the Windermere is one, lies three-quarters of a mile or thereabouts to the east and northeast. The only good way to go from the Loop to the University is to take a suburban train of the Illinois Central Railroad from Michigan Avenue at Randolph Street or at Van Buren Street, and get off at the station marked "55th–56th–57th Street," which is adjacent to the Windermere. At the 56th-Street exit from this station there is a taxi-stand to the east and a bus-stop to the west (be sure to ask the bus-conductor whether he goes to Ellis Avenue and 55th Street); or one may get to the Research Institutes Building at 5630 Ellis Avenue by walking along 56th Street a little over half-a-mile westward and turning left into Ellis Avenue. People coming to Chicago by train should detrain at Englewood, if they come by the Pennsylvania; at Englewood or Woodlawn, depending on which train they take, if they come by the New York Central; at Woodlawn if they come by the Illinois Central, and at the downtown termini if they come by other railroads. Note that Chicago taxicabs make extra charges for extra passengers.

The **registration desk** will be located in the Research Institutes Building at 5640 South Ellis Avenue. Members and guests are required to register and to pay the modest registration fee of one dollar, in return for which they will get a copy of this Bulletin and the satisfaction of having contributed toward the cost of this meeting. Banquet tickets will be sold at the desk. Blackboards will stand in the neighborhood of the desk, and will bear notices of messages, the titles of post-deadline papers if there are any, and possibly news of changes in the arrangements described in this Bulletin. Messages will not be accepted from any who have not registered. Research Institutes 480 and Eckhart 133 will be available for conversation and relaxation.

Our **Division of High-Polymer Physics** has arranged two Symposia, one wholly of its own (structure of some polymers of biological interest) and the other in conjunction with our Division of Solid-State Physics (some physical properties of crystalline solids); and it has assembled three sessions of contributed papers.

Our **Division of Solid-State Physics** has set up five Symposia, and when to these is added the joint affair with DHPP, one sees that there was not a possibility of freeing even one of these from competition with contributed papers in the field of the Division. The subjects are: color centers, paramagnetic and ferromagnetic resonance, classical solid-state physics, crystal imperfections, and magnetism at very low temperatures.

Our **Division of Chemical Physics** has provided two Symposia, one on applications of magnetic resonance to problems in molecular physics and the other on the many-body problem, and a session of contributed papers.

The **1958 Oliver E. Buckley Lecture** by this year's Oliver E. Buckley Solid-State Physics prize winner, N. Bloembergen, is entitled "Nuclear magnetic resonance in solids," and it will be given on Friday afternoon at 1:45. By delaying the opening times of the other Friday-afternoon sessions we have spared other speakers from having to compete with this singular event, and by advancing slightly the opening times of the Friday-morning sessions we have left a reasonable interval for luncheon.

Invited papers apart from the Symposia are sparse, there being so many comprised in the Symposia: but five have been included in the programme, and those who will give them are J. L. Birman, W. S. Boyle, D. J. Hughes, Hermann Statz, and G. Weinreich.

Two hundred and sixty contributed papers make this the record March meeting to date, as mentioned already. Of the twenty-four sessions in which they are dispersed, eighteen are devoted wholly to solid-state physics, and this topic encroaches on most of the other six—three in high-polymer physics, one in chemical physics, one in cryogenics, and one short session which contains the whole of the contribution of nuclear physics to this meeting. (Contrary to precedent, we invited not even one speaker in nuclear physics to address this convention, feeling that we should do an injustice by offering to any such physicist too small an audience.) The problems of classification (in the old sense of this word) seemed even harder than those which arise at a more diversified meeting, and they have not been perfectly solved even despite the invaluable aid of solid-state physicists who desire to remain anonymous. If a paper appears in what seems the wrong session, this may be due to ignorance; it may also occur because the appropriate session is already as long as it should be, or because the subject has two aspects (or more than two) and it is doubtful which should determine the classification. It is interesting to note that magnetic resonance, nuclear and electronic, now pervades the whole of physics so thoroughly that at this congress there is not a single half-day out of the six on which it does not figure.

The **banquet of the Society** will be held on Friday at 6:30 P.M. in the Quadrangle Club, 1155 East 57th Street at the corner of University Avenue. The after-dinner speakers will be L. A. Kimpton, Chancellor of the University of Chicago, and A. W. Lawson. Tickets at $4.25 will be on sale at the registration desk, and a form for advance reservation is printed on page 155 of this Bulletin. You are very specially asked to make use of this form, for at this meeting we encounter the "guarantee hazard" in an aggravated degree. Hotels can often adapt themselves to the number of ticket-buyers even a few hours before the dinner, but the situation of a club is different, and the Quadrangle Club requires a guaranteed estimate on the evening before the meeting begins. If we estimate too low some people will be disappointed, but if we estimate too high···. Please aid by clipping out the form on page 155, filling it, and mailing it as directed.

A **social affair** is being arranged by the three Divisions for the Thursday afternoon from five to seven. Present outlook is that it will be held in the Quadrangle Club with beer, edibles, and a price tag of the order of $1.25. If we get details in time, a form for advance reservation for this event may be included in this Bulletin: otherwise, see what is said on the blackboards by the registration desk. Though this affair is a responsibility of the Divisions, it will be open to all who come to the meeting. Even nuclear physicists may come without trepidation, and in fact will be welcomed. To those who have attended previous Chicago meetings it will come as a pleasant surprise to hear that cocktails may now be purchased at the Quadrangle Club.

The **Council of the American Physical Society** will meet at 11:45 on Thursday morning in the Quadrangle Club, unless contrary notification is sent to its members. Come to the top of the stairs.

Business Meetings of the three Divisions—DHPP, DSSP, DCP—will be held at the times and places shown in the Epitome and in the main text of the programme.

The **calendar of prospective meetings and deadlines,** extending through 1958, appears on page 152. Here also appears the "must" reading, *viz.*, the instructions for the preparation of abstracts. Commendation is lavished on the great majority of our abstract-writing members, who are conforming pretty well to our rules and pleas. Most often

neglected at present are the request that abstracts be typed as a single paragraph, and the plea for duplicate copies. Belated abstracts are getting to be rarer, but we still occasionally receive them, sometimes in envelopes postmarked on deadline-day itself or even later. We try to return these before long, but do not guarantee to do so. Anyone who posts his abstract on deadline-day or even the day before must be assuming that our rules are just empty words. This is a mistaken assumption.

Post-deadline ten-minute papers pertaining to very recent achievements of very special importance will be considered for admission to a special supplementary programme if the abstracts are received at the office of the Society (the address below) not later than Friday, March 21. Papers which missed the deadline narrowly are not eligible for this privilege. The names of such papers as may be accepted will be found on the blackboard near the registration-desk, and the papers will be scheduled for presentation at the end of Session E or possibly elsewhere (see blackboard).

Errata will be published in a later issue of this Bulletin if received not later than Monday, April 7, at the office of Miss Ruth Bryans, American Institute of Physics, 335 East 45th Street, New York 17, New York. Do not send your abstract defaced with corrections: write out the corrections in the form "Instead of . . . read. . . ." Do not add anything. Errata are not published either for introducing new data, or for restoring material that was cut out because the abstract was too long.

KARL K. DARROW, *Secretary*
American Physical Society
Columbia University
New York 27, New York

EPITOME OF THE 1958 MARCH MEETING AT CHICAGO

(Personal names are those of invited speakers, except at the ends of lines where they are those of halls. DHPP stands for Division of High-Polymer Physics; DSSP for Division of Solid-State Physics; DCP for Division of Chemical Physics).

Thursday Morning

10:00 A. DSSP: Color centers; Gourary, Compton, Gordon, Känzig. Mandel.
9:30 B. DHPP: Structure of polymers of biological interest; Hall, Bear, Rich. Eckhart.
9:30 BA. Diverse topics in solid-state physics. Pathology.
9:30 C. Transport properties and impurities in Si and Ge; Weinreich. Kent.
10:00 D. Nuclear physics. Social Sciences.

Thursday Afternoon

2:00 E. Transport phenomena, mostly theory. Post-deadline papers, if any. Pathology. James.
2:00 F. DSSP: Paramagnetic and ferromagnetic resonance; Rado, Jeffries, Suhl, Townes. Mandel.
2:00 FA. Dislocations; whiskers. Social Sciences.
2:00 G. High-polymer physics; Business Meeting of DHPP. Eckhart.
2:00 GA. Lattices and structures; Hughes. Cobb.
2:00 H. Breakdown, impact ionization, noise in semiconductors. Kent

Thursday Afternoon at 5:00

Social Affair. Quadrangle Club.

Friday Morning

9:15 J. Photoconductivity. Eckhart.
9:15 JA. Irradiation effects I. Pathology.
9:15 K. DHPP and DSSP: Physical properties of crystalline solids; Mark, Weertman, McCrum, Vineyard. Mandel.
9:15 L. DCP: Applications of magnetic resonance in molecular physics; Weissman, Karplus, McConnell. Business Meeting of DCP. Kent.
9:15 LA. Semiconducting compounds; Birman. Social Sciences.
9:45 M. Metals I (mechanical properties). Cobb.

Friday Afternoon

1:45 N. Oliver E. Buckley Lecture by N. Bloembergen; Mandel.
2:30 P. DSSP: classical solid-state physics; Warren, Huntington, Jacobsen, Krumhansl. Mandel.
2:40 Q. Metals II. Cobb.
2:40 QA. Ionic crystals. Social Sciences.
2:40 R. Various topics in semiconductor physics. Kent.
2:40 SA. High-polymer physics. Eckhart.

Friday Evening

6:30 Banquet of the Society; Kimpton, Lawson. Quadrangle Club.

Saturday Morning

9:30 T. High-polymer physics (mostly rubbers). Eckhart.
9:30 TA. Cryogenics; Boyle. Social Sciences.
9:30 U. DSSP: Crystal imperfections; Nowick, Walker, Koehler, Gilman. Mandel.
11:59 Business Meeting of DSSP. Mandel.
9:30 UA. Paramagnetic resonance. Oriental.
9:30 V. Luminescence; surface effects; Statz. Pathology.
9:30 VA. DCP: The many-body problem; Alder, Montroll, Brueckner, Huang. Kent.

Saturday Afternoon

2:00 W. Chemical physics. Kent.
1:30 X. DSSP: Magnetism at very low temperatures; Hudson, Meyer, Wheatley, Silsbee. Mandel.
1:45 XA. Irradiation effects II. Pathology.
1:30 Y. Ferromagnetic and nuclear magnetic resonance. Oriental.
2:00 Z. Mostly solid-state theory. Eckhart.

PROGRAMME

THURSDAY MORNING AT 10:00

Mandel Hall

(R. J. MAURER presiding)

DSSP Symposium

Color Centers

A1. Wave Functions for Electron-Excess Color Centers in Alkali Halide Crystals. BARRY S. GOURARY, *Applied Physics Laboratory, The John Hopkins University.* (30 min.)

A2. Polarized Light as a Tool for Studying the Symmetry Properties of Color Centers. W. DALE COMPTON, *U. S. Naval Research Laboratory.* (30 min.)

A3. Color Centers and the Mechanical Properties of Crystals. ROBERT B. GORDON, *Yale University.* (30 min.)

A4. Paramagnetic Resonance of Trapped Holes in Alkali Halides. WERNER KÄNZIG, *General Electric Research Laboratory.* (40 min.)

THURSDAY MORNING AT 9:30

Eckhart 133

(J. D. FERRY presiding)

DHHP Symposium

Structure of Some Polymers of Biological Interest

B1. Electron Microscopy of Natural and Synthetic Macromolecules. C. E. HALL, *Massachusetts Institute of Technology.* (40 min.)

B2. A Comparison of the Structure of Certain Natural and Synthetic Fibers. R. S. BEAR, *Iowa State College.* (40 min.)

B3. Structure of the Synthetic Polyribonucleotides. A. RICH, *National Institutes of Health.* (40 min.)

THURSDAY MORNING AT 9:30

Pathology 117

(CYRIL S. SMITH presiding)

Diverse Topics in Solid-State Physics

BA1. Li Induced Ferromagnetism in MnSe. R. R. HEIKES AND W. D. JOHNSTON, *Westinghouse Research Laboratories.*—In a recent paper[1] an attempt was made to induce ferromagnetism in MnO by a partial substitution of Mn by Li. Such a substitution should produce Mn in both the divalent and the trivalent states, thereby allowing the possibility of a double exchange[2] type coupling. However, experimentally it was found that $Li_xMn_{1-x}O$ remained antiferromagnetic and was semiconducting with a high activation energy (0.5 ev). It has been suggested[3] that this activation energy is caused by the local lattice distortion introduced by the trivalent ion. Further, it is expected that the lattice distortion, and the associated activation energy, can be decreased or eliminated by replacing the anion by one of higher electronic polarizability. In an attempt to verify this suggestion, the $Li_xMn_{1-x}Se$ system was studied. It has been found that the introduction of 10% Li into the MnSe lattice converts the material to a ferromagnetic one with metallic type conductivity.

[1] W. D. Johnston and R. R. Heikes, J. Am. Chem. Soc. **78**, 3255 (1956).
[2] C. Zener, Phys. Rev. **82**, 403 (1951).
[3] R. R. Heikes and W. D. Johnston, J. Chem. Phys. **26**, 582 (1957).

BA2. Remarks on a Magnetically Dilute System. H. SATO AND A. ARROTT, *Ford Motor Company,* AND R. KIKUCHI, *Wayne State University.*—The behavior of the transition from paramagnetism to ferromagnetism as a function of composition in magnetically dilute systems is of particular importance in understanding the origin of ferromagnetism.[1] In order to interpret experimental results on such a system properly, the theoretical understanding of the behavior of some simplified system is very helpful. Here we are interested in a system in which a fraction of the lattice points of a given crystal are occupied by magnetic ions. We assume further an exchange

interaction only between nearest neighbors of magnetic ions. Earlier work[2] on similar systems indicates a linear relationship between Curie point and concentration for low concentrations of magnetic ions. This conclusion is the result of the averaging processes characteristic of the approximations adopted. Several methods for avoiding this difficulty are devised, and the Curie point, the susceptibility *vs* temperature curve, etc., are calculated for such a system. It is found that the Curie point starts at a finite concentration for a random distribution of magnetic ions.

[1] A. Arrott, Fifth International Conference on Low Temperature Physics and Chemistry (1957), p. 11.
[2] L. Neel, Ann. phys. 5, 23 (1936); R. E. Behringer, J. Chem. Phys. 26, 1504 (1956).

BA3. Small Magnetic Field Mapping Probes of Thin Semiducting Films. JOHN W. BUTTREY, *Armour Research Foundation.*—A probe for mapping magnetic fields with high resolution has been constructed using the Hall effect in thin semiconducting films. Germanium films have been used to produce a probe with an active area of approximately 10 μ and having a sensitivity of about 100 oe. Measurements on thin films of indium antimonide indicate that it is at least twenty times as sensitive as germanium for this purpose because of a much lower noise level which is the sensitivity-limiting factor in these devices.

BA4. Polarization Reversal in $BaTiO_3$ Samples with Aqueous LiCl Electrodes. ROBERT C. MILLER, *Bell Telephone Laboratories.*—Single crystal $BaTiO_3$ samples with aqueous LiCl electrodes in place of the customary noble metal electrodes are observed to undergo polarization reversal at low electric fields in a manner very much analogous to magnetization reversal in ferromagnetic materials.[1] It is shown that polarization reversal under these conditions can take place by the expansion of a few switched domains through extensive sideways 180° domain wall motion. The switching current is in general quite irregular, and sharp decreases in the current are usually coincident with one or more ferroelectric Barkhausen pulses. This switching behavior is very different from that encountered with noble metal electroded crystals, for then one observes many Barkhausen pulses, small domains,[2] and therefore a limited amount of sideways 180° domain wall motion.

[1] C. Kittel and J. K. Galt, *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1956), Vol. 3.
[2] W. J. Merz, Phys. Rev. 95, 690 (1954).

BA5. A New Interpretation of the Permeability of Porous Materials.* S. MROZOWSKI, *University of Buffalo.*—Many attempts to explain the permeability of porous materials to the flow of fluids in terms of the parameters describing the structure were made in the past, no explanation succeeding in covering satisfactorily all the main features of the flow mechanism. In this paper a model of a consolidated bed of granular material is discussed, for which the main resistance to flow is due to resistances at and around the constrictions (baffles), the approach being an exact analog of the one used in the treatment of the problem of flow of electric and heat currents through porous media.[1] For this model the permeability is a product of two factors: one corresponding to the resistance of a constriction, and the other representing the statistics of the distribution of constrictions throughout the material. It is shown that experimental results obtained by Seldin[2] for the flow of gas through beds of carbon powders can be well interpreted in terms of such a model, the experimental data requiring that the permeability of a single constriction be proportional to 7/3 power of its diameter.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] S. Mrozowski, "Proceedings of the First and Second Conferences on Carbon, University of Buffalo (1956)," p. 195.
[2] E. J. Seldin and S. Mrozowski, *Proceedings of the Third Conference on Carbon* (Pergamon Press, Inc., New York) (to be published).

BA6. Electronic Properties of Hydrogenated Carbons and Polycrystalline Graphites.* A. CHABERSKI AND S. MROZOWSKI, *University of Buffalo.*—Since it is believed that excess holes are present in carbons and graphites as a result of trapping π electrons at the crystallite boundaries, it seemed very promising to try to hydrogenate the peripheries of the crystallites and thus force the electrons out of the traps and back into the π band. Atomic hydrogen was pumped across a sample of a soft carbon heat treated to 1900°C for about 25 hr; this treatment brought a change in the Hall constant but in the direction of an *increase* in number of excess holes (chemical attack leading to an increase of the internal surface). However, Mr. F. G. Reick, of Diversified Technology, Inc., East Syracuse, New York, has kindly helped us by successfully hydrogenating our carbon samples (1900° and 2250°) using a method of his own. Measurements have shown that hydrogenation leads to changes in the Hall constant corresponding to changes occurring with increase in degree of graphitization; the electrical resistivity and magnetoresistivity changing in the direction corresponding to a decrease in graphitization. Subsequent heat treatment to 1600°C in a nitrogen atmosphere removes most of the hydrogen from the samples and leads to changes in the reverse direction, as expected.

* Work supported by the Office of Naval Research.

BA7. Changes in Microstructure of Copper and Iron Produced by High-Intensity Shock. CYRIL STANLEY SMITH, *University of Chicago.*—Through the cooperation of Messrs. Duff, Walsh, Fowler, and others in Group GMX6 of the Los Alamos Laboratory, samples have been subject to plane shock waves of intensities up to 600 kilobars and recovered substantially undamaged. Copper, above about 200 kilobars, develops markings which occur most frequently at 30° to the shock direction and are probably mechanical twins. The double shock in iron at pressures in the range of 130–350 kilobars[1] produces microstructural change in two stages: a simple Neumann banding, occurring most frequently at 45° to the shock direction, followed by a superimposed more complex structure which is probably the result of a change to a more close-packed structure in the second shock. Inclined shocks permit distinction between the effects of compression and rarefaction. In iron, interaction between the reflected rarefaction wave from the first shock and the ongoing second shock, if near a free surface, gives a very sharp microstructural interface, proving that the shock front is narrow and little affected by local grain orientation. Microscopic measurement of this interaction zone gives relative shock velocities.

[1] Bancroft, Peterson, and Minshall, J. Appl. Phys. 27, 291 (1956).

BA8. Shock-Excitation of Powdered Solids. R. W. NICHOLLS, W. H. PARKINSON, AND M. D. WATSON, *University of Western Ontario.*—The luminosity which arises from the interaction between helium-driven shock waves in argon (Mach 2–7.5) and grains of powdered material of astrophysical interest (oxides and meteorites) has been studied spectroscopically. Diatomic molecular band systems dominate the spectra at low Mach numbers (~4) while atomic lines dominate the spectra at higher Mach numbers (~7.5). Time-resolved spectra in emission and also in absorption have been obtained which indicate that the reflected shock wave plays a major role in the excitation process. Microscopic and x-ray studies of the shock-excited grains have been undertaken in order to clarify some of the collision processes responsible for the luminosity. Severe ablation of grains is present, and in some cases macroscopic color changes associated with surface chemical reactions have been observed (e.g., Fe_2O_3

turns from red to black with the surface formation of Fe_3O_4 globules, PbO turns from yellow to grey with the liberation of lead). The interrelation between this work and meteor physics will be discussed.

BA9. Generation of Heat in the Formation of Cryptocrystalline Structures during Vitrification of Aqueous Colloids.* B. LUYET, C. KROENER, AND G. RAPATZ, *The American Foundation for Biological Research.*—In a previous report Luyet and Rapatz showed that devitrification in aqueous solutions, as indicated by the appearance, upon warming, of a cloud of submicroscopic particles, occurs only in material which has been previously invaded by a flimsy cryptocrystalline structure. We were able to detect the generation of heat involved in the formation of this structure, during the vitrification, by rapid cooling, of layers about 30 μ thick of 30% gelatin gels. A constantan-copper thermal junction, of one-mil wire, inserted in the layer of gelatin and connected to a recording galvanometer (the Visicorder of the Heiland Company) gave freezing curves in which a distinct rise, in the form of a sharp peak, appeared while the layer was being cooled at a rate of some 700° per sec in an iso-pentane bath at −115°. The rapidly cooled gel remained transparent, and, when it devitrified, upon being warmed to −10°, it generated considerably more heat.

* Aided by the Office of Naval Research.
[1] B. Luyet and G. Rapatz, Bull. Am. Phys. Soc. Ser. II, 2, 342 (1957).

BA10. Photographic Emulsion Studies by the Sequence Exposure Experiment.* J. H. ENNS AND E. KATZ, *University of Michigan.*—The basic principles of the photographic sequence experiment[1] will be reviewed briefly, and experimental data for several emulsion types will be presented and discussed. The results show that the just developable grain of a commercial emulsion, color-sensitized in the blue, is a perfect (or nearly so) absorber of all incident photons at 4358 A. More extensive data (varying average grain size, total and internal image development) will be presented for a pure silver bromide emulsion of minimum sulfur sensitization. An interesting result for this emulsion type is, among other things, an increase in the absorbed photons determined for the just developable grain with increasing grain size or increasing sensitivity. This effect will be discussed on the basis of dispersed latent image formation due to an increase in the number of effective trapping centers per grain.

* Work supported by the Air Research and Development Command.
[1] J. H. Enns and E. Katz, J. Opt. Soc. Am. 47, 758 (1957).

BA11. Emissivity and Transmissivity of Infrared Materials at Elevated Temperatures. D. MERGERIAN, *Armour Research Foundation.*—The spectral emissivity and transmissivity of samples of fused silica and synthetic sapphire have been determined at four temperatures between 100°C and 1000°C, and for KRS-5 at 100°C and 400°C for wavelengths between 1.0 μ and 13.0 μ, employing a cylindrical blackbody cavity and a Perkin-Elmer double pass monochromator. Measurements of refractive index by a minimum deviation method and of absorption coefficient over the same wavelength and temperature range are presently being conducted. These data will be employed to determine emissivity and transmissivity as a function of sample thickness.

BA12. Tristable Optical Feedback Storage Light Amplifier.* H. O. HOOK AND E. E. LOEBNER, *Radio Corporation of America.*—Bistable storage cells using an electroluminor-photoconductor light-amplifying circuit with optical feedback have been described.[1,2] Tristable operation of this circuit is possible if the power supply has two well-separated frequency components of roughly equal amplitudes not necessarily harmonically related. The requirement for attaining tristability is that without feedback the light amplifier have a region of gamma greater than one for each electrical frequency component and that these be well separable by a region of gamma less than one. Theory and experiment will be described. This technique is capable of rendering halftone storage in existing solid-state storage panels[3] and may be extendable to more than three stable operating states.

* This work was supported by the U. S. Army Signal Engineering Laboratories.
[1] E. E. Loebner, Phys. Rev. 100, 1239 (1955).
[2] E. E. Loebner, Proc. Inst. Radio Engrs. 43, 1897 (1955).
[3] Loebner, Hook, and Darling, a paper at Electron Devices Meeting, Washington, D. C., November 1, 1957.

BA13. Low-Temperature Phase Transition of the Hexamethylbenzene Crystal and the Spectral Changes Accompanying It.* O. SCHNEPP, *Duke University.*—The hexamethylbenzene crystal undergoes a phase transition at about 110°K at which temperature a discontinuity has been observed in its specific heat curve. The near ultraviolet spectra of single oriented crystals of this substance have been studied in polarized light in the neighborhood of the transition temperature. A drastic and discontinuous change of the spectra is observed to accompany the phase transition at a temperature of 110±3°K. The crystal plane investigated is the *bc* plane in which the molecules are viewed edge-on so that the polarization components represent the absorption in the molecular plane and perpendicular to that plane. The low-temperature spectrum of the crystal has been analyzed.[1] In this spectrum the in-plane component represents the forbidden benzene spectrum while the out-of-plane component has an allowed structure and a prominent O−O band. In the high-temperature spectrum, on the other hand, the in-plane component is an allowed spectrum with very simple structure. The out-of-plane component is identical in structure to the in-plane component but has extremely low intensity. The spectral change at the transition point is interpreted as indicative of a distortion of the molecule such that only twofold symmetry axes remain.

* Sponsored by the National Science Foundation.
[1] O. Schnepp and D. S. McClure, J. Chem. Phys. 26, 83 (1957).

BA14. Role of Lammellar Twinning in the Decomposition of KN_3 and NaN_3 Crystals.* R. W. DREYFUS, *Picatinny Arsenal,* AND PAUL W. LEVY, *Brookhaven National Laboratory.*—Previously we have shown that, when KN_3 and NaN_3 crystals are examined with a polarizing microscope, brightly colored birefringent bands are observed *providing* that the crystals have been subjected to thermal or mechanical shock.[1] Most bands are associated with steps on the surface that occur where planes passing diagonally through the crystal [(110) in NaN_3, (112) in KN_3] intersect the surface. In a few instances "ramps," not steps, are found. These are caused by lamellar twinning. From the twin geometry and the indexes of refraction the retardation associated with each twin may be computed and is found to agree well with the measured values. Also, the angle between the "ramp" and the surface agrees with that predicted from a diagram showing the atom movements required to form the twin. Since twinning has been detected in only a few cases, other mechanisms, such as slip, also may be operating. In this case distortion along the slip plane causes the birefringence. Also, steps could be formed by twinning. When these crystals are decomposed by heat or radiation, most of the decomposition occurs at the step or "ramp."

* Supported jointly by Picatinny Arsenal and the U. S. Atomic Energy Commission.
[1] R. W. Dreyfus and P. W. Levy, Bull. Am. Phys. Soc. Ser. II, 1, 140 (1956).

THURSDAY MORNING AT 9:30

Kent 107

(H. Y. FAN presiding)

Transport Properties and Impurities in Si and Ge

C1. Imperfection Conduction in Silicon.* R. K. RAY, T. A. LONGO, AND K. LARK-HOROVITZ, *Purdue University.*—Impurity conduction behavior has been reported[1] for some silicon samples. A systematic survey for boron-doped samples gives a series of characteristic curves for the temperature dependence of Hall coefficient and resistivity. A few Al-doped samples were also measured. For boron-doped samples the temperature for onset of impurity conduction, indicated by Hall maximum and corresponding decrease in resistivity slope, changes between 18 and 100°K for samples of increasing impurity concentration. The behavior indicates similarity to detailed observations on germanium. Ranges of impurity concentration seem to indicate different conduction mechanism for impurity concentration greater than about 5×10^{18} imp/cc and lower than about 10^{16} imp/cc with transitional behavior in between. The mobility is low in the impurity region. Low-concentration samples give mobility values lower by order of magnitude compared to high-concentration samples in the impurity conduction range. A very striking example of imperfection conduction has been observed for an originally degenerate *p*-type sample in which the Fermi level has been moved into the forbidden band by deuteron irradiation.

* Work supported by a Signal Corps contract.
[1] G. A. Swartz, Bull. Am. Phys. Soc. Ser. II, 2, 134 (1957).

C2. Magnetic Field Dependence of the Hall Coefficient in Silicon.* F. J. REID, A. C. BEER, AND R. K. WILLARDSON, *Battelle Memorial Institute.*—Hall coefficients of *p*-type silicon specimens from pulled single crystals were measured as functions of magnetic field from 500 to 20 000 gauss at temperatures of 80, 200, and 300°K. Room-temperature resistivities ranged from 30 to 300 ohm-cm, with minority carrier lifetimes from 60 to 430 microseconds. At 80°K, $R_{\sigma B}$ values ranged from 8000 to 11 000 cm²/v-sec. Variations in Hall coefficients at 80°K with magnetic field were about 10%, agreeing satisfactorily with theoretical results of Beer and Willardson.[1] This theory assumes spherical light-mass bands and warped heavy-mass bands with warping parameters, density of states ratios, and mobility ratios consistent with cyclotron resonance predictions. The importance of considering a mixed scattering process is illustrated. Departures from the theory were noted at the higher temperatures. These may result from certain considerations discussed by Long.[2] At 80°K, the Hall coefficient was independent of electric field below 0.1 v/cm. At higher fields the resistivity was either independent of electric field or exhibited a dependence similar to that of the Hall coefficient.

* Work supported in part by the Electronics Research Directorate, Air Force Cambridge Research Center.
[1] A. C. Beer and R. K. Willardson (to be published).
[2] D. Long, Phys. Rev. 107, 672 (1957).

C3. Lifetime in *p*-Type Silicon. J. S. BLAKEMORE, *Honeywell Research Center.*—It has been reported previously[1] that photoconductive decay lifetime in *p*-type silicon at room temperature does not vary linearly with excess carrier density. These measurements are now extended to the temperature range 200–400°K. Theoretical examination has been given to a model of photoconductive decay via a numerous single species of recombination center, such that deviations occur from the simplest Shockley-Read behavior, but the properties of this model do not account for the experimental results. The latter are more readily represented by conceding the presence of at least two kinds of recombination center. Those accounting for more than half of the recombination in all our specimens, tentatively identified as gold, provide a donor level 0.34 ev above the valence band for which $\tau_{p0}/\tau_{n0}=13$. The supplementary recombinative process is much more strongly donor-like with $\tau_{p0}/\tau_{n0}>100$ and is associated with a level some 0.54 ev below the conduction band. Variability of the temperature dependence between various crystals suggests that this process may be composite, with contributions from chemical residues of various transition elements.

[1] J. S. Blakemore, Bull. Am. Phys. Soc. Ser. II, 2, 153 (1957).

C4. Magnetoresistance of *n*-Germanium at Low Temperature.* R. A. LAFF AND H. Y. FAN, *Purdue University.*—At liquid helium temperature, germanium usually shows impurity band conduction with low magnetoresistance. The magnetoresistance effect of free electrons in *n*-type crystals has been studied by exciting the electron from donor impurities with long wavelength infrared radiation. Oriented samples ($N_D=4\times10^{13}$) were measured with fields of 500 to 3500 oersteds and as a function of angle between H and I at 2200 oersteds. The quantities $\Delta\rho/\rho_0H^2$ increased with decreasing field and had not yet reached constant values at 500 oersteds. Under the assumption of isotropic relaxation time the data could not be fitted by applying the high field theory with $\tau\propto\epsilon^{-\frac{1}{2}}$ usually assumed for lattice scattering. With $\tau\propto\epsilon^{\frac{1}{2}}$ (impurity scattering) the data could be fitted by using $m_{\|}/m_{\perp}=20$ and $\mu_H=4.5\times10^4$ cm²/volt-second. This mobility is compatible with the concentration of compensating impurities as estimated from the Hall mobility at 77°K. Magnetoresistance measurements at 77°K, made in the conventional manner, show low field behavior below 2000 oe. The value of $m_{\|}\tau_{\perp}/m_{\perp}\tau_{\|}$ deduced from Hall and magnetoresistance data is 10 ± 1. The symmetry relations are obeyed to the extent that $c/b\sim-1.25$.

* Work supported by the Office of Naval Research.

C5. Temperature Dependence of the PME Effect in Germanium. S. GOLDSTEIN, H. METTE, AND W. W. GÄRTNER, *U. S. Army Signal Engineering Laboratories.*—The photomagnetoelectric (PME) effect[1] in germanium has been investigated as a function of temperature above 300°K, under conditions of pure surface generation of excess carriers. Samples of different impurity content and of different thicknesses have been measured. The observed temperature variation of the PME effect is explained by the Shockley-Read[2] mechanism of carrier recombination, and by the temperature dependence of carrier densities and mobilities.

[1] W. van Roosbroeck, Phys. Rev. 101, 1713 (1956).
[2] W. Shockley and W. T. Read, Jr., Phys. Rev. 87, 835 (1952).

C6. Temperature and Electric Field Dependence of Hole Lattice Mobility. E. M. CONWELL, *Sylvania Electric Products.*—It has been shown that the $T^{-2.3}$ dependence of lattice mobility observed for holes in germanium can be obtained by combining acoustical and optical mode scattering, the latter with a characteristic temperature of 300°K.[1] This temperature dependence can also be obtained with a characteristic temperature for the optical modes of 400°K, the value indicated by neutron scattering experiments.[2] A calculation of the variation in lattice mobility with electric field intensity has been carried out, incorporating optical modes with this

characteristic temperature and acoustical modes. The simple model of band structure was used. The optical modes were found to dominate the energy loss even at low fields for temperatures as low as 78°K. The effect of not assuming equipartition of energy for the acoustical lattice oscillators will be discussed.

[1] H. Ehrenreich and A. W. Overhauser, Phys. Rev. **104**, 649 (1956).
[2] Pelah, Eisenhauer, Hughes, and Palevsky, Phys. Rev. **108**, 1091 (1957).

C7. Penetration of Cu into Ge Containing Ni and Cu Precipitates. A. G. TWEET AND W. W. TYLER, *General Electric Research Laboratory.*—Penning[1] has observed that Cu^{64} will diffuse into Ni-doped Ge at 500°C to produce Cu concentrations of $\sim 17C'$, where C' is the equilibrium value. He has suggested that vacancies formed by the dissociation of substitutional Ni atoms into vacancy-interstitial pairs during Ni precipitation are responsible for this. We have shown that Cu concentrations of $>100\,C'$ can be achieved at 500°C even if Ni precipitation is complete before the Cu diffusion begins. We suggest that Ni precipitates rather than vacancies may cause the enhanced Cu penetration. The Cu concentration C, after diffusion at 500°C, is consistent with $C = C_0 \operatorname{erfc}[x/2(D_{eff}t)^{\frac{1}{2}}]$ where $D_{eff} \approx 10^{-8}$ cm²/sec and $C_0 \approx C_{Ni}$, the total concentration of Ni already present in the sample. The excess Cu is not electrically active. Similar measurements using samples with Cu precipitates in place of Ni precipitates show that an exchange of Cu between the surface and the interior of the sample takes place at 500°C, also with $D_{eff} \approx 10^{-8}$ cm²/sec. Samples with dislocation densities of $\sim 10^6$ cm^{-2}, with presumably fewer free vacancies and aggregates, yielded the same results, for Cu precipitates, as more perfect specimens. At 400°C, $D_{eff} \ll 10^{-10}$ cm²/sec in all cases and no appreciable Cu^{64} penetration is observed.

[1] P. Penning, Philips Research Repts. (to be published).

C8. Effect of Doping on the Diffusion of Impurities in Germanium.* M. W. VALENTA, *University of Illinois.*—The diffusion coefficients of indium, antimony, arsenic, and tin were measured in As-doped, intrinsic, and Ga-doped germanium over a temperature range from 760°C to 880°C. Donor diffusivities in the As-doped (about 10^{19} atoms/cm³) samples ranged from 1.3 to 2.7 times the corresponding ones in intrinsic germanium, and those in the Ga-doped (about 10^{19} atoms/cm³) ranged from 0.55 to 0.65 times those of the intrinsic samples. The acceptor diffusivity also changed with doping in the same direction (greater in *n*-type than *p*-type germanium), but the change was appreciably smaller than that observed for donors. Likewise, tin has a larger diffusion coefficient in *n*-type than *p*-type germanium. The observed changes are in the direction predicted by a vacancy mechanism[1] in which the donors form complexes[2] with negative vacancies, and acceptors form complexes with both neutral and negative vacancies. The heavily-doped single crystals were prepared by W. W. Tyler of the G. E. Research Laboratory.

* This work was supported in part by the U. S. Air Force through the office of Scientific Research of the Air Research and Development Command and in part by a grant from Motorola, Inc.
[1] M. W. Valenta and C. Ramasastry, Phys. Rev. **106**, 73 (1957).
[2] A. B. Lidiard, Phil. Mag. **46**, 815 (1955); **46**, 1218 (1955).

C9. Effect of Doping on the Diffusion of Impurities in Silicon.* M. F. MILLEA,† *University of Illinois.*—The diffusivities of P, Sb, Sn, and In in "intrinsic" ($\sim 10^{18}$ impurity atoms/cm³ or less), heavily doped *n*-type ($\sim 5\times 10^{19}$ atoms/cm³), and heavily doped *p*-type ($\sim 2\times 10^{20}$ atoms/cm³) silicon have been measured to obtain information on the way diffusion takes place. The measured diffusivities of P and Sb in *n* type are twice their values in intrinsic silicon; their diffusivities in *p* type are one-half those in intrinsic silicon. These changes are in the direction expected for vacancy diffusion.[1] The diffusivity of Sn in *n* type is about 50% larger than in intrinsic, whereas in *p* type it is about equal to that in intrinsic silicon. Opposite changes are found for the diffusivity of indium; it is about 6 times larger in *p* type and about 50% lower in *n* type than in intrinsic silicon. Possible diffusion mechanisms for substitutional impurities in silicon will be discussed in the light of these and other data.

* This work was supported in part by the U. S. Air Force through the Office of Scientific Research of the Air Research and Development Command and in part by a grant from Motorola, Inc.
† Now at Pacific Semiconductors, Inc.
[1] M. W. Valenta and C. Ramasastry, Phys. Rev. **106**, 73 (1957).

C10. Theoretical Calculation of Distribution Coefficients of Impurities in Germanium and Silicon. KURT WEISER, *RCA Laboratories.*—The distribution coefficients, k of Group III, IV, and V impurities in germanium and silicon have been calculated by evaluating the terms of the equation developed by Thurmond and Struthers.[1] The dominant term was found to be the heat of solution in the solid. This term was broken down into a strain component and an electronic component, the former arising from a difference in size of the impurity atom and the host atom, the latter due to a difference in binding energies. The strain energy was calculated by considering the compression and bending of the bonds as successive nearest neighbors of the impurity atom are displaced from their normal position. The electronic component was calculated by estimating the difference in binding energy of an impurity atom in its own lattice compared to that in the host lattice. A small additional energy term had to be included for ionizable impurities. Agreement between theoretical and experimental values was better than a factor of three for all but a few exceptions.

[1] C. D. Thurmond and J. D. Struthers, J. Phys. Chem. **57**, 831 (1953).

Invited Paper

C11. Acousto-Electric Effect in Germanium. G. WEINREICH, *Bell Telephone Laboratories.* (30 min.)

THURSDAY MORNING AT 10:00

Social Sciences 122

(H. L. ANDERSON presiding)

Nuclear Physics

D1. Resonant Excitation and Damping of Betatron Oscillations.* L. C. TENG, *Argonne National Laboratory.*—Resonant excitation and damping of the radial betatron oscillation of the ion beam in a circular accelerator have been employed for beam extraction and injection.[1-3] For accelerators with fixed magnetic field this is the only method so far available. The

effect of a general resonant forcing term on a linear harmonic oscillation is studied by the first-order perturbation method. The resulting expressions are sufficiently general and compact to enable the design of the most efficient extractor and the optimum injector which gives maximum filling of the available phase space area. Several numerical examples and methods of producing, in practice, the required forcing terms will be discussed. The combined employment of the resonant excitation for extraction and of the resonant damping for injection will enable the continual transfer of an ion beam from one circular accelerator to another in the manner proposed earlier.[2,3]

* This work performed under the auspices of the U. S. Atomic Energy Commission.
[1] J. L. Tuck and L. C. Teng, *170-Inch Synchrocyclotron Progress Report No. 111* (The University of Chicago, Chicago, Illinois, 1950), Chap. VIII; J. L. Tuck and L. C. Teng, Phys. Rev. 81, 305 (1951).
[2] L. C. Teng, Phys. Rev. 100, 1247 (1955).
[3] L. C. Teng, Rev. Sci. Instr. 27, 106 (1956).

D2. Reactions Induced in U^{235} with Protons, Deuterons, and Alpha Particles.* J. R. HUIZENGA, J. WING, W. J. RAMLER, D. J. HENDERSON, AND A. L. HARKNESS, *Argonne National Laboratory.*—U^{235} has been bombarded with protons, deuterons, and alpha particles accelerated in the Argonne 60-in. cyclotron. Excitation functions have been measured for the production of: Np^{235} and Ba^{140} with H^+ of energies up to 10.7 Mev; U^{237}, U^{239}, Np^{234}, and Np^{235} with D^+ of energies up to 21.7 Mev; Np^{239}, Pu^{238}, Pu^{239}, Pu^{240}, Pu^{241}, and Ba^{140} with He^{++} of energies up to 43.5 Mev. The excitation function for the reaction $U^{238}(d,p)U^{239}$ is very similar to that obtained for the reaction $Pb^{208}(d,p)Pd^{209}$. The yields of the plutonium isotopes were determined by spiking the samples with Pu^{242} and measuring isotopic ratios with a mass spectrometer. Employing the values of Γ_f/Γ_n derived from neutron- and gamma-induced fission data, the excitation functions for the compound nucleus reactions are reasonably well calculated with the assumption that Γ_f/Γ_n is independent of excitation energy.

* Based on work performed under the auspices of the U. S. Atomic Energy Commission.

D3. New Area Method for Analyzing Neutron Resonances.* J. P. MARION AND L. M. BOLLINGER, *Argonne National Laboratory.*—A new method for determining the Breit-Wigner parameters of neutron resonances from transmission data has been developed. It is an area method which uses the partial area above a limited range of energy rather than the whole area above a transmission dip, as has been used in the past. To make this new approach possible, the partial areas A_g' above transmission dips between energies $(E_0-\epsilon)$ and $(E_0+\epsilon)$ were calculated.[1] Values of A_g' were obtained for $n\sigma_0$ ranging from 0.1 to 150, for Δ/Γ from 0.2 to 10 and for ϵ/Δ from 0.5 to 7.5. These results were used to construct a series of families of curves of A_g'/Δ *vs* $n\sigma_0$ for various fixed values of Δ/Γ and ϵ/Δ. The application of these curves to resonance analysis is discussed. The principal advantage of the new method as compared to the older area method is that resonance parameters can be determined with greater accuracy. Secondary advantages are that individual parameters can be determined from the results of measurements on a single sample and that distortions in resonance shapes cause a less serious error in derived parameters.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] Calculation on the AVIDAC by A. J. Strecok.

D4. Neutron Spectra from $A^{40}(p,n)K^{40}$.* R. E. HOLLAND, F. J. LYNCH, AND KINEO TSUKADA,† *Argonne National Laboratory.*—The energies of neutrons from the $A^{40}(p,n)K^{40}$ reaction were measured using a time-of-flight technique with an externally pulsed beam from the Argonne electrostatic accelerator. Over a wide range of proton bombarding energies, only neutrons corresponding to transitions to the second and third excited states of K^{40} were observed. Preliminary Q values for these transitions are -2.345 ± 0.010 Mev and -3.105 ± 0.01 Mev, respectively. When these data are combined with the excitation energies of these states, one obtains a Q value of -2.312 ± 0.015 Mev for the transitions to the ground state and a mass difference of 1.530 ± 0.015 Mev between A^{40} and K^{40}. This is slightly higher than the 1.51 ± 0.02 Mev obtained by averaging data from other reactions and from mass spectroscopy.[1]

* This work performed under the auspices of the U. S. Atomic Energy Commission.
† Now at Japan Atomic Energy Research Institute.
[1] Way, King, McGinnis, and Van Lieshout, "Nuclear Level Schemes, $A=40-A=90$," U. S. Atomic Energy Commission. Report TID 5300.

D5. Gamma Radiation of Co^{56}.* T. AZUMA,† F. T. KOKOSZKA, D. R. CARTWRIGHT, AND J. D. KURBATOV, *The Ohio State University.*—Carrier free Co^{56} was chemically separated from proton activated iron. The following gamma rays (with intensities in parentheses), as previously reported, were observed with a single channel spectrometer and their coincidences were verified: 0.845(100), 1.24(50), 1.75(17), 2.02(10), 2.60(10), 3.25(15), and 3.47(1) Mev. Gamma rays of 2.11 and 2.99 Mev were resolved by coincidence and had relative intensities of 8 and 2. Sum peak contributions were considered in the evaluation of intensities. In addition the 2.11 ± 0.03 Mev gamma ray was found to be the transition between the 2.958- and 0.845-Mev energy levels. The angular correlation of 0.845- and 2.11-Mev gamma rays was measured giving the anisotropy as 0.683. This value was larger than that of pure gamma-ray transition 2(1)2(2)0. Then the 2.12-Mev gamma ray has the mixing ratio, E_2/M_1, of 3.6%. Experimental evidence indicates that the 1.35-Mev and 1.03-Mev peaks, which were observed, are sum peaks with annihilation radiation although low-intensity gamma rays of these energies are not precluded. Energy levels of Fe^{56} as previously reported were confirmed.

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
† On leave from University of Osaka.

D6. Gamma Rays from Rhodium-101.* C. W. TOWNLEY, H. W. PARLETT, D. C. GLENN, AND J. D. KURBATOV, *The Ohio State University.*—Enriched Ru^{101} was activated with protons[1] and carrier free Rh^{101} was chemically separated for study with a scintillation spectrometer and lens type magnetic spectrometer. Two isomers, as previously reported, were observed: the first with $T\frac{1}{2}$ determined to be 4.52 ± 0.05 days and the second with long life. One isomer of short life emits the following gamma rays, observed by internal conversion electrons and direct measurement of gamma rays except for a few gamma rays which were resolved by coincidence only: 144 ± 5 kev and 155 ± 5 kev (both very strong, resolved by coincidence) 302 ± 4 kev (very strong), 546 ± 6 kev (weak), 236 ± 4 kev (very weak), 538 ± 5 kev (weak) and some others that are very weak. The isomer of long life emits 129 ± 2 kev (strong), 192 ± 3 kev (strong), 325 ± 5 (weak), and other gamma rays that are very weak. A partial scheme of disintegration will be presented.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] Activation was made in the Washington University cyclotron. Cooperation of J. T. Morgan and G. W. Farwell in this research is acknowledged.

D7. Angular Dependence of 500-kev Bremsstrahlung Polarization.* J. W. MOTZ AND R. C. PLACIOUS, *National Bureau of Standards.*—With 500-kev electrons incident on thin beryllium and gold targets, the polarization of photons near the limit (420 to 500 kev) of the bremsstrahlung spectrum has been measured as a function of the photon emission angle with a polarimeter[1] that depends on the polarization sensitivity of the Compton process. The Born approximation

bremsstrahlung theory[3] predicts that the polarization of these photons (450 kev for example) has a reversal as the emission angle increases: for small angles the polarization is parallel to the emission plane with a peak value of 0.78 at 20 degrees, and for large angles the polarization is perpendicular to the emission plane with a peak value of 0.31 at 130 degrees. The results of the measurements confirm the existence of such a reversal. However, the measured values of the polarization show quantitative differences from the shape of the theoretical polarization curve and are significantly smaller than the predicted values at the peak angles.

* Work supported by the U. S. Atomic Energy Commission.
[1] J. W. Motz, Phys. Rev. 104, 557 (1956).
[2] R. L. Gluckstern and M. H. Hull, Jr., Phys. Rev. 90, 1030 (1953).

D8. $\pi^- - P$ Interactions at 600 Mev. W. D. WALKER, R. R. CRITTENDEN, J. H. SCANDRETT, AND W. D. SHEPHARD, *University of Wisconsin and Brookhaven National Laboratory*, AND J. A. BALLAM, *Michigan State University and Brookhaven National Laboratory.**—We have exposed the Wisconsin propane bubble chamber to π^- mesons of energies 450, 600, 700 Mev at the cosmotron. The active volume of the chamber is approximately 5 in. $\times$12 in. $\times$11 in. The central volume of the chamber is viewed with two cameras whose axes are at right angles. The right angle stero system makes accurate angle measurements possible. We have made preliminary measurements of the $\pi^- - P$ elastic scattering at 600 Mev. The available angular resolution makes it possible to discriminate quite well against the numerous quasi-elastic scatterings of π^- with protons bound in carbon. At this energy the elastic, inelastic, and charge exchange cross sections are 18 mb, 10 mb, and 9 mb, with about 15% errors.

* Work partially supported by the U. S. Atomic Energy Commission, Wisconsin Alumni Research Foundation, and the National Science Foundation.

D9. Configuration Mixing and the *j-j* Coupling Nuclear Shell Model.* STEVEN A. MOSZKOWSKI, *University of California, Los Angeles.*—The *j-j* coupling shell model implies that there are certain geometrical relations among binding energies and excitation spectra of neighboring nuclides. Such relationships are satisfied quite well by a number of nuclei,[1] sometimes even in regions where one would not expect a *j-j* coupling model to be applicable. We have studied the effect of certain idealized forms of two-body interactions on level spectra, taking into account configuration mixing involving the first excited particle state. The interaction is assumed to be a combination of a quadrupole-quadrupole term[2] which tends to give rise to collective quadrupole deformation and of a particular short-range "separable" interaction[3] which gives a pairing energy in singlet *S*-states, but none in other two-particle states. While the configuration mixing changes the level schemes, the validity of the geometrical relations is affected much less, especially by the pairing interaction. Thus a *j-j* coupling model (with "renormalized" interactions) may be fairly adequate for energy calculations, unless the configuration mixing is large.

* Supported in part by the Office of Ordnance Research.
[1] R. D. Lawson and J. L. Uretsky, Phys. Rev. 106, 1369 (1957); I. Talmi and R. Thieberger, Phys. Rev. 103, 718 (1956).
[2] J. P. Elliott (to be published).
[3] Y. Yamaguchi, Phys. Rev. 95, 1628 (1954).

THURSDAY AFTERNOON AT 2:00

Pathology 117

(V. A. JOHNSON presiding)

Transport Phenomena, Mostly Theory

E1. Generalized Variational Principle for Transport Phenomena. G. E. TAUBER, *Western Reserve University and Franklin Institute Laboratories.*—A variational principle, equivalent to the Boltzmann transport equation for the particle distribution function, has been formulated by Kohler.[1] If deviations from equilibrium of the phonon distribution functions are also taken into account, a system of coupled integral equations results, for which a variational approach was suggested by Ziman.[2] Recently, Dorn obtained a variational principle for this case and applied it to include the effect of longitudinal polarized lattice vibrations for spherical energy surfaces. Also, Moliner and Simons developed a variational principle which includes the effect of an external magnetic field. It will be shown that a generalized variational principle can be formulated which takes the phonon distribution functions and the external magnetic field into account, and is valid for an arbitrary direction of the electric field and polarization of the lattice vibrations, and does not depend on any special form of the energy surface. The various transport coefficients, both for thermoelectric and thermomagnetic phenomena, are then obtained by the Ritz method in terms of infinite determinants without requiring an explicit solution of the transport equations.

[1] M. Kohler, Z. Physik 124, 772 (1948); 125, 679 (1949).
[2] J. M. Ziman, Can. J. Phys. 34, 1256 (1956).

E2. Weisskopf-Wigner Perturbation Theory and the Transport Equation. MELVIN LAX, *Bell Telephone Laboratories.*—A derivation is given of Weisskopf-Wigner perturbation theory that does not assume exponential decay of the occupancy of the initial state. It is well known that such an exponential decay cannot be valid for small times. The method of derivation demonstrates explicitly the transition from an oscillatory region at small times to an exponential decay that becomes asymptotically valid at large times. Extension of the Weisskopf-Wigner method from second-order to higher order perturbation theory is indicated. A derivation of the Pauli transport equation based on Weisskopf-Wigner perturbation theory is given.

E3. Statistical-Mechanical Theory of Transport in Fluids.* HAZIME MORI, *Brown University.*—We consider a nonequilibrium liquid in thermal contact with a heat bath. The state approaches an equilibrium via local equilibrium states specified by local temperatures and chemical potentials changing in time. The ensemble is slightly deviating from the local equilibrium ensemble, $\rho_l = Z^{-1} \exp[-\beta(H+R)]$. This deviation can be determined by applying Liouville's equation with no interaction with the heat bath to the change in a short time.[1] The Poisson bracket of R with the Hamiltonian H becomes the integral of

$$\dot{R}(\mathbf{x}) = \mathfrak{I}_v : \mathbf{X}_v + \mathbf{J}_T \cdot \mathbf{X}_T + \Sigma_i (\mathbf{J}_d{}^i \cdot \mathbf{X}_d{}^i + J_r{}^i X_r{}^i)$$

over coordinate space, where X's are the affinities[2] and J's dynamical quantities corresponding to the conjugate fluxes.

On this basis, the entropy production and the phenomenological equations of motion are derived with explicit expressions for the transport coefficients, which differ, even in the classical case, from Green's.[4]

* Supported in part by the U. S. Air Force.
[1] H. Mori, J. Phys. Soc. Japan 11, 1029 (1956).
[2] Hirschfelder, Curtiss, and Bird, *Molecular Theory of Gases and Liquids*, Eq. (11.1-26) and Table 11.2-1.
[3] M. S. Green, J. Chem. Phys. 22, 398 (1954).

E4. Surface Transport Theory. JAY N. ZEMEL, *U. S. Naval Ordnance Laboratory.*—A solution of the Boltzmann equation is found for carriers traveling in the space charge region at the surface of a spherical band semiconductor under the action of crossed electric and magnetic fields. Expressions for the conductivity and Hall coefficient are derived from this solution assuming an energy independent mean free time τ, and an arbitrary potential shape in the space charge region. The conductivity term for zero magnetic fields is identical to the expression found by Schrieffer.[1] If the space charge field E_z is constant and equal to its value at the surface E_{zs}, then the surface Hall coefficient R_s can be expressed in closed form,

$$R_s=\left[\frac{N_s q\mu_b^2}{\sigma_s^2}\right]\frac{\langle\mu_s^2\rangle}{\mu_b^2};\quad \frac{\langle\mu_s^2\rangle}{\mu_b^2}=\left\{1-\frac{2\alpha}{\pi^{\frac{1}{2}}}-(1-2\alpha^2)e^{\alpha^2}\operatorname{erfc}\alpha\right\},$$

where N_s is the number of surface carriers, σ_s is the surface conductivity, and μ_b is the bulk carrier mobility. α is defined as $(2m^*KT/qE_{zs}\tau)^{\frac{1}{2}}$. The reduced "Hall" mobility $(\langle\mu_s^2\rangle/\mu_b^2)^{\frac{1}{2}}$ agrees to within 10–20% of the reduced "conductivity" mobility μ_s/μ_b of Schrieffer. Because of the various assumptions, the magnetoresistance vanishes in this model.

[1] J. R. Schrieffer, Phys. Rev. 97, 641 (1955).

E5. Analysis of Multicarrier Galvanomagnetic Effects. J. W. MCCLURE, *National Carbon Research Laboratories.*—Under certain conditions (given in the following) the diagonal and off-diagonal parts of the transverse magnetoconductivity tensor for a single carrier are related by Kramers-Kronig type relations. The relations have previously been used to check the consistency of data. However, the sign of the carrier enters into the relations in such a way that effects of positive and negative carriers can be entirely separated when both types of carriers are present. The number of negative and positive carriers and the average conductivity mobilities of each can be found by evaluating simple integrals of magnetoconductivity tensor components against magnetic field strength. The necessary conditions are that (1) all cyclotron orbits be circular, (2) a relaxation time exists and is constant on each orbit, and (3) high-field quantum effects can be ignored. If these requirements are to be met for only one orientation of the magnetic field, then the effective mass and relaxation time may depend upon both the coordinate in k space parallel to the magnetic field and the energy. If the requirements are to be met for all orientations of the magnetic field, then the effective mass and relaxation time can depend upon energy only. The most important experimental requirement is that the data cover a wide range of magnetic fields.

E6. Determination of Galvanomagnetic Coefficients for Arbitrary Two-Dimensional Sample Geometry. R. M. BROUDY, *National Carbon Research Laboratories.*—The geometrical correction factors for the galvanomagnetic coefficients of any shape two-dimensional figure can in principle be determined analytically by a conformal transformation to a "Hall parallelogram" for which the acute angle is (90°−Hall angle); this was shown by Wick[1] for some simple configurations. By the present analog technique it is possible to obtain these factors for any shape two-dimensional figure for any electrode size or configuration without analytical computation or use of magnetic field. The analog of the conformal transformation is performed by constructing a figure of the same shape as the sample measured and a "Hall parallelogram" (with assumed Hall angle) out of any uniform conducting material. The requirements for a conformal transformation are met by making both figures of equal resistance. Equipotential plots locate equivalent electrode positions and thence geometrical correction factors are easily found. The process is repeated until assumed and computed Hall angles agree. This method has particularly interesting application to high-mobility semiconductors such as InSb.

[1] R. F. Wick, J. Appl. Phys. 25, 741 (1954).

E7. De Haas-van Alphen Type Oscillatory Magnetoresistance Dependence upon Magnetic Field Orientation in a Graphite Single Crystal. D. E. SOULE, *National Carbon Research Laboratories.*—Magnetoresistance measurements have been extended on a graphite single crystal at 4.2°K in order to study the dependence on the magnetic field orientation. A series of angles were investigated ranging from the transverse orientation ($H\|$hexagonal axis) down to the longitudinal orientation ($H\perp$hexagonal axis). The anisotropy in the magnetoresistance, $\rho_T/\rho_L=3000$. De Haas-van Alphen type oscillations are analyzed to map the Fermi surfaces from the variation of the periods applying the relation due to Onsager.[1] Also, effective mass anisotropies are determined from the magnetic field damping of the respective amplitude components.

[1] L. Onsager, Phil. Mag. 43, 1006 (1952).

Post-Deadline Papers, If Any

THURSDAY AFTERNOON AT 2:00

Mandel Hall

(CHARLES KITTEL presiding)

DSSP Symposium

Paramagnetic and Ferromagnetic Resonance

F1. Excitation of Spin Waves in Ferromagnets. GEORGE T. RADO, *U. S. Naval Research Laboratory.* (40 min.)

F2. Paramagnetic Resonance and Dynamic Polarization Experiments with Radioactive Nuclei. C. D. JEFFRIES, *University of California.* (30 min.)

F3. Amplification of Microwaves by Ferromagnetic Materials. H. SUHL, *Bell Telephone Laboratories.* (30 min.)

F4. Paramagnetic Relaxation at Very Low Temperatures. CHARLES H. TOWNES, *Columbia University.* (30 min.)

THURSDAY AFTERNOON AT 2:00

Social Sciences 122

(THORNTON READ presiding)

Dislocations; Whiskers

FA1. Helical Dislocations and Spiral Etch Pits in Silicon. W. C. DASH, *General Electric Research Laboratory.*—Helical and prismatic dislocations similar in many respects to those found in CaF_2 [1] have been observed in silicon by decoration techniques[2] following heat treatment for several hours at 1200°C. The helices lie in ⟨110⟩ directions and are joined to nonhelical dislocations with random orientations, consistent with the hypothesis that they originated from screws. In addition, randomly distributed hexagonal or circular dislocation loops apparently associated with oxygen precipitates but independent of prismatic loops cast off from helices are frequently observed. A spiral pit with step heights corresponding to the turn spacing is formed upon etching a helix as has been predicted.[3,4] However, observations of orientation, concentration and correlation with known dislocations indicate that not all spiral pits are in this class. Thus caution is essential in associating all spiral pits with helices.

[1] W. Bontinck and S. Amelinckx, Phil. Mag. 2, 94 (1957).
[2] W. C. Dash, J. Appl. Phys. 27, 1193 (1956).
[3] Amelinckx, Bontinck, and Dekeyser, Phil. Mag. 2, 1264 (1957).
[4] S. G. Ellis, Phil. Mag. 2, 1285 (1957).

FA2. Possible Observations of Single Dislocation Generators.* R. S. COLLIER, H. H. MCINTOSH, AND P. GIBBS, *University of Utah.*—1×2×8.5-mm crystals of *n*-type Eagle-Picher germanium were stressed by the slow application of three-point loading.[1,2] At 550°C they were deformed about 25 μ, annealed at 850°C for one hour, deformed at 550°C, annealed at 850°C, etc. Creep properties differed widely from specimen to specimen, but reproduced on successive runs with the same specimen. Some showed "glide jumps" of about 10 μ which repeated at the same stress on each cycle. No plastic flow could be detected at room temperature, but occasional pulses were observed in the electrical conductivity as the stress was applied. In every case tested, a pulse appeared about 0.05 sec before fracture. Pulses are thought to arise with the creation of unsaturated bonds along new dislocation.

* Supported in whole or in part by the U. S. Air Force, monitored by the Aeronautical Research Laboratory, Wright Air Development Center.
[1] Collier, McIntosh, and Gibbs, Bull. Am. Phys. Soc. Ser. II, 2, 371 (1957).
[2] McIntosh, Tucker, and Gibbs, Bull. Am. Phys. Soc. Ser. II, 2, 372 (1957).

FA3. X-Ray Integrated Intensity and Dislocation Content in Germanium. BORIS W. BATTERMAN, *Bell Telephone Laboratories.*—The absolute values of (111) and (333) integrated intensities were measured on both as-grown and plastically deformed germanium single crystals. An undeformed crystal containing 8×10^4 random dislocations gave an integrated (111) reflection only 5% greater than predicted for a perfect crystal, while the theoretical ratio of intensities of ideally imperfect to perfect is roughly a factor of 5. Thus, one can conclude that integrated intensities are not a sensitive measure of random dislocations of densities below $\sim10^6$ cm^{-2}. Pure edge dislocations were introduced by bending and annealing so as to produce arrays of dislocations parallel to [112] and lying in (110) walls. This type of controlled deformation allows one to investigate x-ray properties without having to assume a model of crystalline imperfection. With a view plane perpendicular to the walls, the x-ray reflections were measured with the plane of diffraction both perpendicular and parallel to the dislocation walls. A bent specimen containing 8×10^6 dislocations showed a doubling of intensity over the perfect crystal value when the diffraction plane was perpendicular, and an increase of 15% when parallel to the dislocation walls. Quantitative results indicate that the x-ray mosaic block size is determined not only by the dislocation wall spacing but also by the misorientation of adjacent blocks and the strain within each block.

FA4. Dislocations and Selective Etch Pits in InSb. J. D. VENABLES AND R. M. BROUDY, *National Carbon Research Laboratory.*—We have observed a special type of dislocation etch pit in InSb which illustrates the polarity of the zincblende lattice and the nature of dislocations therein. The dislocation direction and slip plane were found to be ⟨110⟩ and {111} respectively. Dislocations were introduced by plastic bending at 450°C and selective etch pits were observed on {110} faces. The etch pits are "arrow" shaped and all point in the same ⟨100⟩ direction on any one crystal regardless of bending direction. Observation of etch pit distribution patterns on bent crystals and correlation with etch pits on {111} faces show that the {110} pits develop for only one of two possible types of ⟨110⟩ dislocation which exist in the zincblende lattice. These two types can occur because the terminating row of atoms in a ⟨110⟩ dislocation can be either In or Sb.

FA5. Plastic Deformation of InSb.* J. J. DUGA, R. E. MARINGER, AND A. C. BEER, *Battelle Memorial Institute.*—Effects of uniaxial compression were studied on single crystal samples with donor concentrations between 1×10^{14} and 2×10^{16}/cm^3. Hall coefficient, resistivity, magnetoresistance, and dislocation density were determined. For small deformations, the Hall coefficient (at 77°K) remains constant, although resistivity increases. One hour under 500 psi at 300°C decreased the value of $R_H\sigma$ (always measured at 77°K) from 5×10^5 to 8×10^4 cm^2/volt-sec for a specimen with carrier concentration of 1×10^{14}/cm^3. Magnetoresistance mobility was unchanged. Two hours compression at 2000 psi and 190°C converted a sample with 2×10^{14}/cm^3 electrons and $R_H\sigma$ of 3×10^4 cm^2/volt-sec to one with 1×10^{14}/cm^3 holes having $R_H\sigma$ of 5000 cm^2/volt-sec. However, for a sample containing 1×10^{16} carrier/cm^3, carrier densities were constant for compressions of 2000 psi at 300°C up to 20 hours, although $R_H\sigma$ decreased from 120 000 to 26 000 cm^2/volt-sec. For carriers in excess of 5×10^{14}/cm^3, degeneracy complicates use of magnetoresistance to determine mobility. Dislocation densities, revealed by etch pits, increased from 2×10^4 to 1×10^7/cm^2 after 5 hours compression under 2000 psi at 300°C. Resistivities (at 77°K) and dislocation densities initially exhibited a square root dependence on deformation time. Annealing effects on etch-pit densities and electrical characteristics are discussed.

* Supported by the Office of Naval Research.

FA6. Impurity Motion Along Dislocation.* R. N. TUCKER, F. M. WANLASS, G. S. BAKER, AND P. GIBBS, *University of Utah.*—Bending a 0.1 in. diameter corundum rod through 1 cm radius adds 10^7 parallel edge dislocations/cm^2 to those 10^6 random dislocations/cm^3 already present. Boiling 30 min in HCl or NaCl solution presumably adds H or Na impurity. A bump ($Q\sim0.25$, low activation energy) appears in dielectric loss[1] upon heating an H-contaminated, bent, sample to 600°C with E parallel to dislocations. This bump

is absent in cooling from 700°C, but ~14 kcal resonance appears, suggestive of a Bordoni peak. Several (dislocation field effect?) pulses occur in dc conductivity[2] as contamination is driven off by heating (at 400°C for H, 700°C for Na). Presence of Na with H quenches 400°C pulses, indicating a dislocation "plugging" effect. Dislocations mostly terminate at Pt coating in Q test and air in conductivity tests. Evidence for dislocation "short circuits" is found.

[1] Office of Naval Research support.
[2] Wanlass, Tucker, and Gibbs, Bull. Am. Phys. Soc. Ser. II, 2, 371 (1957).
[3] Tucker and Gibbs, Bull. Am. Phys. Soc. Ser. II, 2, 371 (1957).

FA7. Dislocation Sources in LiF Crystals. J. J. GILMAN AND W. G. JOHNSTON, *General Electric Research Laboratory.*—We reported last year that Frank-Read sources play a negligible role in the plastic deformation of LiF crystals. When LiF crystals are stressed above their elastic limits, dislocation loops nucleate in regions of the crystals that do not previously contain dislocations. For some special cases, the heterogeneities that cause this nucleation have now been isolated and identified. These are two kinds of precipitate particles, as well as clusters of radiation defects. The search is continuing for a more general kind of dislocation nucleation catalyst. The catalysts have been isolated by applying short stress pulses to crystals. These pulses allow only enough time for short glide bands to form at each catalyst. In this way, the complex glide-band interactions that occur in slowly stressed crystals are avoided.

FA8. Dislocation Mobility and Plastic Flow in LiF. W. G. JOHNSTON AND J. J. GILMAN, *General Electric Research Laboratory.*—The stress dependence and temperature dependence of dislocation velocity in LiF have been studied by observing the movements of individual dislocations with a multiple etching technique. The velocity is extremely sensitive to the applied stress, varying roughly as the 25th power of the resolved shear stress. The edge components of dislocation loops move about fifty times as fast as the screw components. At constant stress, the velocity varies with temperature as $\exp(-E/kT)$, where $E \approx 0.7$ ev in the temperature range of +26°C to −52°C, for stresses of 300 to 1100 g/mm². In order to relate dislocation mobility to macroscopic deformation, the number of dislocations present must be known. Etch pit counts indicate that the total number of dislocations/cm², n, increases linearly with the total deformation, $\epsilon = \Delta l/l$; so that $n \approx 10^9\ \epsilon$/cm². (The dislocation distribution is inhomogeneous at small deformations.) With this information on numbers of dislocations, and with the velocity-stress data, it is possible to calculate the flow stress for a given strain and strain rate. At small deformations, this calculated flow stress agrees with the observed flow stress.

FA9. Mechanism of Etch Pit Formation of Lithium Fluoride. G. W. SEARS, J. J. GILMAN, AND W. G. JOHNSTON, *General Electric Research Laboratory.*—Dislocation etch pits can be formed on lithium fluoride by a dilute aqueous solution of ferric fluoride. It is proposed that the preferential etching at dislocations is associated with localized dislocation energy. Nucleation of monolayer pits occurs much more rapidly at dislocations than on areas of perfect crystal surface. Ferric fluoride is adsorbed on the lithium fluoride surface and inhibits the solution rate from monolayer steps, so that steep walled visible pits may be formed. The conjectured mechanism has been subjected to a variety of experimental tests. It has only been possible to compare qualitative consequences with experimental observations by reason of the complex transport process from crystal to solution. In no instance has a discrepancy been found between predicted and observed behavior.

FA10. Polygonization of Copper. F. W. YOUNG, JR., *Oak Ridge National Laboratory.*—A method was presented for obtaining electrolytic etch pits which correspond to dislocations in copper doped with ~0.01 atomic percent tellurium. The correspondence between etch pits and edge dislocations was shown to be one-to-one by bending crystals to various radii of curvature and counting the extra etch pits. No way is known, at present, to develop etch pits which correspond to dislocations in 99.999% copper. The polygonization of copper doped with tellurium was followed after annealing at various temperatures both by observing the etch pits and with back reflection x-ray diffraction. Climbing occurred at 500°C and complete polygonization had occurred after annealing two hours at 1000°C. The progress of polygonization of three nominally 99.999% copper crystals, which had been bent, was followed with back reflection x-ray diffraction. Two of the three samples polygonized, but the one which did not was probably the purest of the three. It was concluded that if impurity is necessary in copper for polygonization, only a very small concentration of impurity is required.

FA11. Temperature Dependence of the Dislocation Modulus and Internal Friction in Copper Single Crystals. D. O. THOMPSON AND D. K. HOLMES, *Oak Ridge National Laboratory.*[*]—Measurements of the Young's modulus and internal friction of several copper single crystals have been made as a function of temperature at low-strain amplitudes before and after neutron irradiation. The temperature range used in these experiments is from about 10°K to room temperature. Since the dislocation components of both the modulus, E_D, and the internal friction, Δ_D, are eliminated by irradiation, it is possible to study the temperature dependence of the dislocation components themselves by subtraction. The evidence obtained to date indicates that there may be essentially two kinds of dislocation internal friction background in well annealed samples which may be correlated with the crystal's orientation, or, stated in a different way, crystals of particular orientations are much more difficult to anneal to a residual low-internal friction background. The chief clue from the experimental data for a theoretical understanding of the internal friction process is that for those crystals which show a residually small temperature dependence before irradiation in this range, the product $E_D^2\Delta_D$ is approximately a constant. Implications of this result will be discussed. It will also be shown that crystals which exhibit the simpler internal friction background can be made to show the more complex by rather small amounts of cold work.

[*] Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

FA12. Thermal Properties of Mobile Defects. A. V. GRANATO, *University of Illinois.*—Using simplified models, calculations are made for the contribution of mobile dislocations and small angle boundaries to the specific heat and thermal resistivity of crystals. The specific heat is found to be proportional to T and T^3 and the thermal resistivity approximately to $T^{-7/2}$ and $T^{-9/2}$ for mobile dislocations and mobile small angle boundaries respectively, over a range of low temperatures, but eventually both go to zero as $T \neq 0$. The magnitudes of the effects are such that although the contribution of dislocations to the specific heat of cold worked nonconductors and superconductors should be measurable, that from small angle boundaries should not. The effect of dislocations on the thermal resistivity is large and should compete with boundary scattering for temperatures of the order of 10^{-2} of the Debye temperature with dislocation densities of the order of 10^8 cm^{-2} in specimens of a few millimeters in diameter. The predicted temperature dependence is in agreement with recent measurement on superconducting lead at low temperatures. At present, contributions from mobile boundaries to the thermal resistivity are not excluded as a possibility.

FA13. Observations of Dislocations in Iron Whiskers. R. V. COLEMAN, *General Motors Research Laboratory.*—Etch pits corresponding to dislocations in crystals have been observed by a number of authors using various techniques. This paper will report on the results of using a 4% picral solution to develop etch pits on iron whiskers. Whiskers which have grown with axes in the [100], [110], and [111] directions which faces up to several hundred microns in diameter have been used in these experiments. Etch pits on {100} surfaces have been observed on as-grown, annealed, and plastically deformed whiskers. A random distribution of widely scattered groups of pits were found on some surfaces of as-grown whiskers. Most such surfaces developed no etch pits. In all cases the edges of the crystal etched away forming {140} planes which gradually removed the {100} face. Plastic deformation of the whisker and subsequent etching produced a density of etch pits which increased with the amount of deformation. The number of pits corresponding to a given deformation remained constant with etching time. Deformation of the whiskers was accomplished in one of two ways, either (1) by bending to various radii of curvature in steel dies or (2) by compression along the whisker axis. Annealing the deformed whiskers at 850°C in hydrogen for periods up to forty hours and then etching produced well-defined rows of etch pits showing various stages of climb leading to polygonization.

FA14. Structure and Strength of Graphite Whiskers. R. BACON, *National Carbon Research Laboratories.**—Graphite whiskers, whose discovery was reported at a previous meeting,[1] have now been grown as long as 3 cm, with diameters ranging from less than 1 μ to 10 μ. Through improved techniques, their breaking strengths have been observed as high as 3 000 000 lb per sq in., and it is believed that the true strength is probably still higher. All available evidence indicates that the sheets, of which the graphite layer structure consists, extend continuously along the entire length of the whisker, resulting in essentially single crystal behavior for properties measured along the whisker axis. Direct evidence has been obtained in support of the hypothesis that the structure consists of large graphite sheets rolled up into a tight tube: whiskers have been exploded, yielding "fragments" of much larger diameter than that of the whisker itself.

* A division of Union Carbide Corporation.
[1] R. Bacon and J. C. Bowman, Bull. Am. Phys. Soc. Ser. II, 2, 131 (1957).

FA15. Properties of CdS Whiskers. D. C. REYNOLDS AND L. C. GREENE, *Wright-Patterson Air Force Base.*—It is postulated that whiskers are the result of crystal growth from a single screw dislocation. This provides one with material that is essentially dislocation free. Comparison of various properties of the whiskers with those of the bulk crystals may allow one to determine the effect of dislocations and other structural defects on these properties. Previously CdS whiskers have been grown by Sears. Using a technique basically similar, whiskers of CdS a few microns in cross section and up to 3 cm long have been grown. Optically they appear very perfect. Unusual elastic properties have been observed as is also the case with other types of whiskers. Strains up to 2.4% have been applied without exceeding the elastic limit. They are photoconductive, with the photoconductive peak occurring at 5000 A. They exhibit both the 0.9 μ and the 1.4 μ quenching bands. However, they do not show the phenomenon of edge emission that is found in most CdS crystals. There has been speculation that the edge emission center is a sulfur vacancy. Bombardment of the whiskers with protons of energy approximately 1 Mev has brought out edge emission in the whiskers. This energy is much larger than that required to create both sulfur and cadmium vacancies. The experiment will be continued using controlled energy electrons in an attempt to produce only sulfur vacancies.

THURSDAY AFTERNOON AT 2:00

Eckhart 133

(J. A. SAUER presiding)

High-Polymer Physics

G1. Dynamic Mechanical Properties of Poly-*n*-lauryl Methacrylate.* SHELDON F. KURATH, THEODORE P. YIN, AND JOHN D. FERRY, *University of Wisconsin.*—Values of complex shear compliance ($J'-iJ''$) have been obtained for a fraction of poly-*n*-lauryl methacrylate of weight average molecular weight 0.95×10^6, prepared by Picatinny Arsenal, at 19 temperatures from −40° to 45°C and at frequencies between 24 and 3600 cps, with the Fitzgerald transducer apparatus. The range of J' was from 1.4×10^{-6} to 2.3×10^{-10} cm²/dyne, covering most of the transition from rubberlike to glasslike consistency. Above −28°, the data superposed to form single composite curves when reduced to 25°C with reduced variables. At −35°, a substantial drop in both J' and J'' indicated crystallization. The temperature dependence of the shift factors followed an equation of the WLF form, with $c_1^0=7.52$ and $c_2^0=132.5$ for a reference temperature of 25°. The retardation (L) and relaxation (H) spectra were similar in shape to those of other methacrylate polymers previously studied, though the maximum in H appeared unusually broad. The logarithm of the monomeric friction coefficient (in dyne sec/cm) is −3.62 at 25° and −6.24 extrapolated to 100°. As with the other methacrylate polymers, the dependence of friction coefficient on side chain length at 100° can be largely accounted for by the differences in free volume deduced by Rogers and Mandelkern.

* Supported by the Ordnance Corps, Department of the Army.

G2. Dielectric Behavior of Polyvinyl Stearate at Audio-Frequencies.* MARTIN G. BROADHURST AND EDWIN R. FITZGERALD, *The Pennsylvania State University.*—The complex dielectric constant ($\epsilon^*=\epsilon'-i\epsilon''$) of polyvinyl stearate has been determined in the frequency range 50 to 50 000 cps in a temperature region extending through the melting point. The polyvinyl stearate used has an average degree of polymerization of 400 and melts from a highly crystalline solid to a viscous liquid at a temperature of 51.5°C. The real part of the dielectric constant (ϵ') rises from a value of 2.34 at 50.0°C to 2.89 at 52.0°C. Values of the imaginary part of the dielectric constant (ϵ'') show considerable dispersion at temperatures just below the melting point and jump discontinuously to large values just above the melting point. The values of ϵ'' above the melting point increase with increasing frequency and decrease with increasing temperature indicating the losses in the melt are not of ionic origin. At the same time values

of ϵ' above the melting point do not exhibit sufficient dispersion to account for the losses in terms of dipole rotation.

* A report of work done under contract with the U. S. Department of Agriculture, Eastern Utilization Research Branch of the Agricultural Research Service.

G3. Mechanical Resonance Dispersion in Polyvinyl Stearate at Audio-Frequencies.* EDWIN R. FITZGERALD, *The Pennsylvania State University.*—Measurements of complex shear compliance ($J^* = J' - iJ''$) at frequencies from 50 to 5000 cps have revealed the existence of several sharp resonances in the compliance of polyvinyl stearate (DP 400) as previously described. The effects of temperature and static pressure normal to the direction of the dynamic shearing stresses have now been studied for this material. The two principle resonances observed at 25°C were located at (*1*) 180 and (*2*) 500 cps. At a temperature of 30°C the 180 cps resonance was essentially unchanged, but the second resonance was reduced in magnitude and shifted to 540 cps. At 36°C the first resonance still remained unchanged but the second had virtually disappeared; this situation remained at 42°C. The samples were then returned to 25°C where the original two resonances were again obtained by the reapplication of a slight static pressure (sufficient to give the same percent deformation as originally present). Increasing the static deformation (and hence pressure) resulted in the elimination of the first resonance and a decrease in the magnitude of the second accompanied by a shift to higher frequencies. The results are analyzed in terms of the mechanical model previously applied to resonances found in polytetrafluorethylene.

* A report of work done under contract with the U. S. Department of Agriculture, Eastern Utilization Research Branch of the Agricultural Research Service.

G4. Dynamic Mechanical Behavior of Irradiated Polyethylene. C. W. DEELEY, A. E. WOODWARD, AND J. A. SAUER, *The Pennsylvania State University.*—Samples of "low-density" polyethylene ($\rho = 0.915$ g/cc) subjected to gamma-ray bombardment from a Co^{60} source up to a dosage of 1×10^9 rep and specimens of a "high-density" polyethylene ($\rho = 0.964$ g/cc) irradiated in a nuclear reactor to thermal neutron doses as high as 2.9×10^{18} nvt have been investigated by dynamic mechanical methods from 80°K to 450°K at audio-frequencies. Degrees of crosslinking were estimated from the observed changes in resonance frequency at temperatures where the specimens were "rubber-like." Densities and x-ray crystallinities at 25°C were also measured. The irradiated "low-density" specimens exhibit three damping peaks. Over the dosage range studied the γ peak, found around 165°K, increases in height and area, the β peak in the 270°K region shifts to higher temperatures, and the α peak at about 360°K shifts to lower temperatures with increasing dose. The crosslinking degree is not proportional to dose and to the highest dosages studied there is very little, if any, reduction in crystallinity. For the pile irradiated "high-density" polyethylene and γ peak shows a marked increase in height and area at dosages above 10^{18} nvt. The α peak decreases markedly upon receiving a thermal neutron dose of 0.5×10^{18} nvt. Further changes in this absorption with higher dosages are obscured by the appearance of a β peak which is almost absent in the unirradiated material.

G5. Apparatus for the Measurement of Torsion Modulus and Internal Friction between 4.2 and 100°K. K. M. SINNOTT, *E. I. du Pont de Nemours and Company.*—An apparatus has been constructed to measure the torsion modulus and logarithmic decrement of polymers from 4.2 to 100°K. The apparatus consists of a small torsion pendulum suspended on a rigid support at the bottom of a large glass Dewar vessel. After cooling to 4.2°K with liquid helium, the pendulum warms up at an initial rate of 0.1° per min. Torsional oscillations of the pendulum are excited electronically and recorded photographically. The estimated accuracy of the modulus is ±5.0% and that of the logarithmic decrement is ±3.0%. Measurements of the torsion modulus and logarithmic decrement have been made, from 4.2 to 100°K, on a series of tetrafluoroethylene-hexafluoropropylene copolymers.

G6. Effects of Pressure on the Line Width and the Longitudinal Relaxation Time for Proton Magnetic Resonance in Polyisobutylene.* A. W. NOLLE AND J. J. BILLINGS, *The University of Texas.*—The proton nuclear magnetic resonance line width for polyisobutylene (viscosity average molecular weight, 1.35×10^6) has been investigated at pressures to 1060 kg/cm², for temperatures −100°C to 32°C. Steady-state absorption apparatus, connected to indicate the derivative of the absorption curve, is used. The pressure fluid is nitrogen. At atmospheric pressure, we reproduce the line width *vs* temperature curve of Powles.[1] Under pressure, the curve slides (with small changes in shape) along the temperature axis toward higher temperatures, the displacement being about 32°C for maximum pressure. The correlation time for molecular reorientation is calculated from the line width. The temperature variation of this quantity is much less rapid than that of a_T in the parameter ωa_T which governs dynamic mechanical properties, and corresponds to an activation energy of 3 kcal/mole. The effect of the maximum pressure is, approximately, to add 0.5 kcal/mole to this value. The longitudinal relaxation time, T_1, which was measured by a transient method, is also discussed. T_1 is about 40 msec at room temperature, and, in the range studied, is less affected by pressure than is the line width.

* Supported by the Office of Naval Research.
[1] Powles, Proc. Phys. Soc. (London) **B69**, 281 (1956).

G7. Birefringence Changes During Retraction of Oriented Polystyrene Monofilaments. III. Correlation with Internal Stress Changes. J. F. RUDD AND R. D. ANDREWS, *The Dow Chemical Company.*—The changes in average birefringence and internal stress during retraction at 85°C have been measured for five different oriented polystyrene monofilaments. The data for the different filaments all appear to fall on a single curve when plotted as internal stress *vs* birefringence. Data on internal stress and birefringence obtained for thirteen different oriented filaments (including the foregoing five) in their initial uncontracted state also fall on the same curve. This is in marked contrast with the unsatisfactory results obtained in Part I where it was attempted to relate birefringence to elongation parameters. From this it may be concluded that birefringence is related essentially to internal stress rather than elongation, and in fact provides a direct measure of the internal stress. This simple relation is apparently independent of the stress-time-temperature history of the samples during orientation. Measurements on a filament with very nonuniform birefringence distribution (also studied in Part II) indicate that internal stress should be correlated with area average rather than diameter average birefringence. The internal stress-birefringence curve is not linear, contrary to theoretical predictions based on the kinetic theory of rubber elasticity. Non-Gaussian chain statistics may explain this nonlinearity.

G8. A Free Volume Approach to Polystyrene Melt Viscosity. M. L. WILLIAMS, *Chemstrand Corporation.*—The Doolittle[1] approach to steady flow viscosity assumes $\eta = A \exp B/f$ where A and B are constants independent of temperature and f, the relative free volume, is $v - v_0/v_0$. Here v is the specific volume and v_0 is the occupied volume. Using machine computations, this equation was applied to published data on polystyrene, replacing v by its equivalent $v_g + (dv/dT)(T - T_g)$, where v_g is the specific volume at the glass temperature T_g. The agreement between calculated and observed viscosities is at

least as good, and perhaps better, than that afforded by other existing empirical expressions. The constant B is independent of molecular weight and temperature while v_0 depends slightly on molecular weight. A log-log plot of A against molecular weight M produces two straight lines intersecting at $M=35\,000$. At higher values of M, the slope is 3.4; at lower values, it is slightly greater than one. This treatment separates the melt viscosity of polystyrene into two factors, A, dependent only on structural parameters, and f, which is determined by the specific volume and is a function of temperature.

[1] A. K. Doolittle, J. Appl. Phys. 23, 236 (1952).

G9. Effects of Blending upon the Stress-Relaxation Behavior of Polyvinyl Acetate in the Rubbery Region. KAZUHIKO NINOMIYA, *Kyoto University and University of Wisconsin* (introduced by J. D. Ferry).—Six blended polyvinyl acetate samples were prepared, each by mixing 2 fractionated samples selected from a group whose molecular weights ranged from 8×10^4 to 8×10^5. Relaxation modulus curves in tension were measured precisely from 50°C to 160°C in the rubbery region (10^7 to 10^8 dyne/cm^2) by an automatic relaxometer. For each sample, a composite curve $E_r(t)$ was obtained by reduced variables with the WLF equation, and from this the relaxation spectrum H was derived by the Williams-Ferry second approximation. Assuming that in a blend the contributions of the components to $E_r(t)$ and H are linearly additive by volume these functions were also calculated from data on the individual fractions. Comparison of observed and calculated values showed that the linear superposition of $E_r(t)$ and H by volume was valid, while the contribution of the high-molecular weight component was shifted to the left and that of the low to the right along the log$t$ (or logτ) axis. The amount of shift could be represented fairly well by $n\log\bar{M}_n/\bar{M}_{ni}$, where $\bar{M}_n$ and $\bar{M}_{ni}$ are the number average molecular weight of blended polymer and of its ith component, respectively, and n is a constant, usually unity.

G10. Infrared Spectrum of Polyvinyl Nitrate. S. KRIMM AND C. Y. LIANG, *University of Michigan*.—The infrared spectrum of polyvinyl nitrate has been obtained in the extended region of 70 to 3600 cm^{-1}. Polarized infrared measurements were made on oriented specimens in the range of 350 to 3600 cm^{-1}. Since x-ray diffraction patterns indicate no crystallinity, the analysis has been based on an assumed atactic configuration. With the help of previous studies of high polymer spectra and results obtained on small molecules, it has been possible to make a complete assignment of all of the expected fundamentals. Dichroic measurements have not only permitted a decision on the assignment of the controversial NO_2 rocking and bending modes, but suggest certain details concerning the local configuration of the nitrate group. There seems to be evidence that, although the specimen is not crystalline, a significant proportion of the chains have configurations not far from a planar zig-zag chain.

Business Meeting of the Division of High-Polymer Physics

THURSDAY AFTERNOON AT 2:00

Cobb 110

(W. H. ZACHARIASEN presiding)

Lattices and Structures

GA1. Dynamics of One-Dimensional Ionic Lattices. HERBERT B. ROSENSTOCK, *U. S. Naval Research Laboratory*.—We consider the vibrations of a linear chain of atoms with alternating charge and nearest-neighbor repulsion. The highest frequency is found to occur at a wave number $p\neq\pi$ regardless of how small the Coulomb forces are compared to the short range forces, and the behavior of the dispersion relation for small $q=\pi-p$ is found to be $\omega(q)-\omega(0)=\text{const}\,q^2\ln q$. The nature of the newly introduced singularity in the frequency distribution therefore differs from the usual one-sided inverse square-root peaks found in the absence of Coulomb forces. Implications of results to real ionic crystals will be discussed.

GA2. Theory of Surface Modes of Vibration in Two- and Three-Dimensional Crystal Lattices. RICHARD F. WALLIS, *U. S. Naval Research Laboratory*.—Theoretical expressions have been developed for the frequencies and displacements of the normal modes of vibration for finite two- and three-dimensional alternating diatomic lattices. Only square and cubic lattices are considered. Nearest neighbor Hooke's law forces having both longitudinal and transverse components are assumed. The free boundary condition has been employed rather than the cyclic boundary condition or the rigid boundary condition. The results have been obtained by means of a perturbation theory in which the ratio of the transverse and longitudinal force constants is treated as a small quantity. The use of the free boundary condition leads to the existence of surface modes of vibration in which the displacement amplitude is relatively large for a light atom on a boundary and decreases roughly exponentially toward the interior of the lattice. These surface modes may be classified as face, edge, or corner modes according to whether the displacement amplitudes have maxima at a face, edge, or corner, respectively. Some of the surface modes have frequencies which form a "surface" branch lying within the "forbidden" gap between the acoustical and optical branches.

GA3. Elastic Spectrum of Silicon from the Thermal Diffuse Scattering of X-Rays.* A. LEARN, *M.I.T.* (introduced by B. E. Warren).—Using the Born formulation of lattice dynamics, a study has been made of the vibrations of the silicon structure. The normal coordinates, expressed as independent traveling plane waves, lead to a secular equation of frequency *vs* wave vector, and a general expression for the scattered intensity. The interactions between atoms enter in the form of interatomic force constants. To include interactions of first, second, and third neighbors, nine constants are required. The dispersion of elastic waves and the effect of the two frequency bands are included in the intensity expressions. For longitudinal [100], [110], [111], and transverse [100], [111] waves, the intensity expressions are sufficiently simple to allow a determination of the nine interatomic force constants from the experimental intensity curves. Evaluation of the force

constants appearing in the secular equation permits the computation of a general frequency spectrum. Measurements have been made of the intensity of diffuse scattering from a single crystal of silicon held at room temperature and the evaluation of the nine force constants will be discussed.

* Supported in part by the National Science Foundation.

GA4. Frequency Spectra of Hexagonal Close-Packed Metals. L. J. SLUTSKY, *University of Texas.*—The frequency distribution spectrum of a central force model of the hexagonal close-packed metals has been approximated using solutions of the secular determinant at a mesh of 90 points in the reduced Brillouin zone. Interactions between an atom and its nearest neighbors in and out of the basal (0001) plane were considered, the Hooke's law constants for the two sets of neighbors being designated α and β, respectively. It was assumed that $\beta = \frac{1}{2}\alpha$ and that the axial ratio (c/a) was equal to 1.6. The reduced plot of θ (the equivalent Debye temperature) *versus* temperature calculated for this model is compared with the results of a calculation using force constants obtained from the low-temperature elastic constants of magnesium and with the experimental θ *versus* temperature curves for hexagonal metals with axial ratios considerably less than the ideal value of 1.633.

GA5. f.c.c. Chromium in Thin Films. LEONARD MULDAWER, *Temple University,* AND DOROTHY M. HOFFMAN AND JACOB RISEMAN, *International Resistance Company.*—Thin films of chromium several hundred A in thickness have been deposited on glass *in vacuo* and then annealed in air at 250°C. Electron diffraction patterns showed a well crystallized f.c.c. lattice ($a = 5.6$ A) for the thinner films and a highly distorted α chromium for the thicker film. The lattice parameter for the latter films was about 5% larger than that found for bulk chromium. The appearance of these films and their electrical behavior is metallic at room temperature. Interference methods showed these films to be smooth to within 30 A. The unit cell of this new chromium phase is assumed to contain 12 atoms giving a volume per atom of 14.7 A^3 compared with 12.0 for α chromium and 14.1 for HCP chromium. The obtained results could not be explained in terms of oxide or nitride formation. Gas atoms trapped during the deposition process, and interfering with normal crystal growth may be responsible. The films themselves are stable with respect to their electrical characteristics over a two hundred and fifty degree temperature range. Resistivities are greater than that of the bulk metal and the temperature coefficients of resistance appreciably smaller, becoming negative with decreasing film thickness.

GA6. Anomalous Ordered Structure in the Cu-Au System.* R. E. SCOTT, *M.I.T.* (introduced by B. E. Warren).—In nonstoichiometric compositions in the Cu−Au system, such as 32 atomic percent Au, the equilibrium diagram shows a two phase region extending from about 300° to 345°C. Material annealed in this region shows the superstructure reflections of a Cu_3Au structure, but in addition some of the superstructure reflections have strong satellites. The satellites have been observed from both powder samples and single crystals. In some cases, single crystals show the satellites in only one direction in reciprocal space. The satellites have been produced by starting with a disordered material at high temperature and dropping the temperature into the two phase region, or by starting with a well-ordered material at low temperature showing no satellites and raising the temperature into the two phase region. The ratio of the intensity of satellites to the intensity of the normal superstructure reflection is greatest at the top of the two phase region and approaches zero at the lower boundary. The results are interpreted in terms of alternating antiphase regions with a repetition period of approximately 30 cells.

* Supported by the Office of Naval Research.

GA7. Elastic Wave Velocity Effects on Temperature Diffuse Scattering in Powders. A. PASKIN, *O.M.R.O.*—Warren[1] and and Paskin[2] have developed expressions for the temperature diffuse scattering (TDS) in cubic powders. A simplifying assumption in these calculations is that all elastic waves have the same average velocity. In practice, the longitudinal velocity is found to be about twice the magnitude of the transverse velocity. The effect of such velocity differences has been considered for the one-phonon contribution to TDS. It is found that the shape of the TDS is altered by a lowering of the TDS in the middle region between Bragg peaks and by an increase in the TDS in the region quite close to the Bragg peaks. This change in shape is found to increase the previous estimate of the contributions of TDS to the apparent measured Bragg peaks[2,3] by about 30% and simultaneously to lower the magnitude of TDS between peaks by about 15%. Similar calculations are now in progress to estimate the effect of these velocity differences on the two-phonon contribution[2,3] to TDS.

[1] B. E. Warren, Acta Cryst. 6, 803 (1953).
[2] A. Paskin, Acta Cryst. (to be published); Bull. Pittsburgh Diffraction Conf., Pittsburgh (November, 1957), p. 20.
[3] D. R. Chipman, Bull. Pittsburgh Diffraction Conf., Pittsburgh (November, 1957), p. 21.

GA8. X-Ray Studies of Crystalline Imperfections in Nearly Perfect Crystals. L. V. AZAROFF* AND R. H. BRAGG, *Armour Research Foundation.*—Laue spots in transmission photographs taken under focusing conditions[1] are highly sensitive to lattice misorientations. The intensity distribution in the profile of a focused Laue reflection has the same significance as in a conventional rocking curve. This technique has been extended to permit quantitative studies of crystalline imperfections and procedures have been developed for separating "pure diffraction" effects from the observed effects. Using this method the variation of crystalline imperfection as a function of position in pulled silicon ingots has been determined. The line width β and peak intensity of 111 reflections were found to be roughly proportional and extreme values differ by an order of magnitude. Using the assumption $Nd = \beta^2/9$ lambda^2 the range of Nd, the dislocation density, is about $1\text{–}100 \times 10^8$ cm^{-2}. The lower limit of detectability is about 10^5 cm^{-2}. A brief discussion of the extension to more perfect crystals will be given.

* Now with Illinois Institute of Technology.
[1] A. Guinier and J. Tennevin, Acta Cryst. 2, 133 (1949).

GA9. Neutron and X-Ray Diffraction Studies of Ti-Zr Null-Matrix and Deuterium System. S. S. SIDHU, LEROY HEATON, D. D. ZAUBERIS, AND F. P. CAMPOS, *Argonne National Laboratory.*—A system consisting of Ti-Zr null-matrix, M (= 62 a/0 Ti and 38 a/0 Zr) and deuterium forms two deuterides. The first is formed below 25 a/0 D and co-exists with M up to about 47 a/0 D. The single-phase region extends from 48 to 58 a/0 D and is cubic. The second deuteride exists in the range of 63 to 66.6 a/0 D. It is tetragonal with axial ratio 0.945. The two deuterides co-exist in the region of 60 to 63 a/0 D. The transformations from the hexagonal structure of the matrix to the first deuteride, and from the first deuteride to the second deuteride, are of the first order. Since the metal atoms in the null matrix and its compounds scatter thermal neutrons in opposite phases and hence give no diffraction peaks, the diffraction patterns of the deuterides result entirely from neutrons scattered by the deuterium atoms. This made it possible to determine the deuterium atom lattices, and the deuterium-deuterium, deuterium-metal, and metal-metal atom distances in the structures.

GA10. Scattering of Neutrons by a Classical Liquid.* GEORGE H. VINEYARD, *Brookhaven National Laboratory.*—The scattering of thermal neutrons by a liquid is given in general by the Fourier transform of a time-displaced radial density function. To a reasonable approximation this function can be expressed as a convolution of the ordinary radial density function with a self-diffusion function describing the wandering of an atom from an arbitrary initial position. The neutron scattering cross section then becomes the product of the Fourier transforms of these two functions. One of the transforms is the differential cross section for x-ray scattering and describes interference effects, the other governs the energy changes upon scattering. It is suggested that a fair approximation to the self-diffusion function for classical liquids is a Gaussian with a time dependent width, and the principal features of the time dependence can be surmised from simple models. Asymptotically, the width depends only on the self-diffusion coefficient of the liquid, and inelastic neutron scattering is suggested as a means of determining this coefficient, as well as other features of atomic movement. The accuracy of the static approximation for determining liquid structures by neutron diffraction can also be assessed.

* Work supported by the U. S. Atomic Energy Commission.

GA11. Compton Scattering of X-Rays by Nonspherical Charge Distributions. A. J. FREEMAN, *O.M.R.O. and M.I.T.*—The inherent nonsphericity of atomic charge distributions results in incoherent scattering intensities which are dependent on the orientation of the scattering direction. In the past, however, the Compton scattering has been calculated with the assumption of a spherically symmetric charge distribution. This paper presents a general mathematical procedure for calculating the incoherent scattering for atoms including both the effects of the nonsphericity of the atom and all the exchange terms in the Waller-Hartree[1] theory. Applications to a number of atoms have been made by these methods using one-electron function wave functions which are solutions of the Hartree-Fock self consistent field equations. These results will be presented and comparison with other calculations (and where possible with experiment) will be made.

[1] I. Waller and D. R. Hartree, Proc. Roy. Soc. (London) **A124**, 119 (1929).

Invited Paper

GA12. Investigation of Lattice Vibrations by Scattering of Cold Neutrons. D. J. HUGHES, *Brookhaven National Laboratory.* (30 min.)

THURSDAY AFTERNOON AT 2:00

Kent 107

(E. BURSTEIN presiding)

Breakdown, Impact Ionization, Noise in Semiconductors

H1. Effect of Dislocations on Breakdown in Silicon *p-n* Junctions. A. G. CHYNOWETH AND G. L. PEARSON, *Bell Telephone Laboratories.*—The light emission patterns of silicon diffused *p-n* junctions at breakdown have been compared with the etch pit patterns that reveal dislocations. It is concluded that avalanche breakdown microplasmas occur preferentially where dislocations pass through the junction. In narrow *p-n* junctions large numbers of dislocations result in enhanced internal field emission and, consequently, a soft reverse characteristic. A good correlation is found between the nature of the light emission pattern (spots for avalanche breakdown, glow for field emission) and the quality of the reverse characteristic. Possible reasons why breakdown occurs preferentially at dislocations will be discussed. Peculiar singularities observed in the light emission patterns of some junctions were found to coincide with crystal abnormalities revealed in the etch patterns.

H2. Low Field Electrical Breakdown in Indium Phosphide. M. C. STEELE, *RCA Laboratories.*—A study of the electrical properties of *n*-type InP has revealed a reversible low field breakdown at 4.2°K. It has all the features of the impact ionization phenomenon previously found in Ge[1] and *p*-type InSb.[2] Breakdown occurred at 9.1 v/cm in a sample having $\sim 10^{16}$ electrons/cc at exhaustion. This field was obtained with both dc and pulse measurements. From resistance *vs* temperature data the activation energy of the unknown impurity involved is estimated to be 3.5×10^{-3} ev. The resistivity was 0.26 ohm cm at 295°K and 140 ohm cm (prior to breakdown) at 4.2°K. The Hall mobility of another piece of the same crystal[3] increased from 5000 cm²/v/sec at 290°K to 20 000 cm²/v/sec at 77°K. Results on other InP crystals will also be presented.

[1] Sclar, Burstein, Turner, and Davisson, Phys. Rev. **91**, 213 (A) (1953).
[2] R. Bray, Phys. Rev. **100**, 1262 (A) (1955).
[3] M. Glicksman (private communication).

H3. Microwave Carrier Heating and Impact Ionization of Impurities in Germanium.* KARLHEINZ SEEGER, *University of Illinois* (introduced by J. Bardeen).—Deviations from Ohm's law have been measured in germanium between 80 and 300°K by extending the method used by Morgan[1] to microwave field intensities of 10^4 v/cm. In agreement with dc measurements of Ryder[2] and others on *n*-type germanium, the resistivity increases with field intensity E and the drift velocity saturates at high fields. No distinct $E^{\frac{1}{2}}$ region occurs, contrary to Ryder's results. In the low-field region the effects of various carrier concentrations have been investigated. With zinc-doped germanium at 80°K a resistivity decrease has been observed even at microwave fields down to the order of 1 v/cm. In this region the resistivity change is proportional to the square of the field and may be due to hole heating in the impurity scattering range. The large resistivity decrease at fields near 10^4 v/cm is considered to be caused partly by impact ionization of holes from the 0.097 ev Zn acceptor level.

* Supported by the U. S. Air Force Office of Scientific Research and Signal Corps.
[1] T. N. Morgan, Bull. Am. Phys. Soc. Ser. II, **2**, 265 (1957).
[2] E. J. Ryder, Phys. Rev. **90**, 766 (1953).

H4. Possible Franck-Hertz Effect in *n*-Type Germanium at Low Temperatures. SEYMOUR H. KOENIG, *IBM Watson Laboratory.*—At helium temperatures, electrons in the con-

duction band of Ge can be heated to mean kinetic temperatures of 100°K or more, with attendant impact ionization of neutral donor impurities. For fairly pure material, a plateau is observed in the variation of both current density and reciprocal Hall constant with electric field.[1] In previous work[1] this had been attributed to a maximum in the mobility, as the dominant scattering mechanism shifted from ionized impurity to lattice scattering. Recent data on more pure material, in which the mobility maximum occurs at lower electric fields (and lower electron temperature), still indicate a plateau at roughly the same electron temperature as was previously indicated. The electric field dependence of the Hall coefficient as well as the variation of the electron-ionized donor capture cross section with electric field[2] indicate a hiatus in the rate of increase of electron temperature with electric field, suggesting the onset of a process that absorbs power from the electron distribution. Arguments suggesting that this may well be the equivalent of the classic Franck-Hertz effect, i.e., non-ionizing excitation of neutral impurities, will be discussed.

[1] S. H. Koenig and G. R. Gunther-Mohr, J. Phys. Chem. Solids **2**, 268 (1957).
[2] W. Schillinger and S. H. Koenig, Bull. Am. Phys. Soc. Ser. II, **3**, 113 (1958), following abstract.

H5. Thermal Capture, Impact Ionization, and the Electrical Conductivity of *n*-Type Germanium below 10°K. W. SCHILLINGER AND S. H. KOENIG, *IBM Watson Laboratory.*—The electric field dependence of the low-temperature electrical conductivity of germanium is determined in the main by a variation in n, the density of conduction band electrons. The steady state value of n for a given electric field is determined by a balance of the generation and recombination rates for these carriers. The processes involved are thermal generation, impact ionization, and their inverses, all of which are dependent on lattice temperature, electron temperature, or both. The cross section for the inverse of thermal generation, capture of an electron by an ionized donor, has been measured as a function of lattice temperature from 4°–10°K both for thermal electrons and for various electron temperatures. The cross section for thermal electrons measured at 4.2°K is $\sim 10^{-11}$ cm^2, or $\sim$100 times geometrical for the donor ground state. If a power law is fitted to the lattice temperature variation of the cross section for thermal electrons, the power is 1.5 ± 0.5. The large cross section suggests that processes similar to those discussed by Lax are involved. The variation of this cross section with electron temperature, and its relation to the temperature and electric field variation of conductivity will be discussed. The possibility of observing Auger recombination (the inverse of impact ionization) will be discussed.

H6. Crystalline Imperfections and $1/f$ Noise in Semiconductors.* JAMES J. BROPHY, *Armour Research Foundation.*—The $1/f$ noise level of single crystal silicon and germanium is found to depend on crystalline imperfection density, as measured by x-ray line broadening. Random edge dislocation densities of the order of 10^7 cm^{-2} are found in as-grown silicon crystals and the noise level is found to decrease with increasing imperfection density. The magnitude of the noise is of the same order as found in n-type germanium. In germanium, the noise level increases greatly with imperfection densities produced by plastic deformation.

* Work supported by the Office of Naval Research.

H7. Ambipolar Carrier Density Fluctuations in Germanium.* K. M. VAN VLIET AND J. E. HILL, *University of Minnesota.*—At room temperature and above $g-r$, noise in germanium is caused by spontaneous fluctuations in generation and recombination of electrons and holes, where $\Delta n \approx \Delta p$. At field strengths, such that the drift times of the carriers are smaller than the lifetime, a modification of the spectrum compared to the spectrum under nearly thermal equilibrium is anticipated. In contrast to the Davydov-Gurevich description[1] of this effect it is presently believed that the ambipolar drift time rather than the hole or electron drift time is the quantity that determines the spectrum. The effect has been calculated by solving the stochastic equation governing the ambipolar transport of carriers. Measurements were made to detect the effect in n- and p-type germanium samples with a reasonable lifetime. For near-intrinsic crystals an oscillatory behavior of the spectrum as predicted by the theory was observed; the calculated ambipolar mobility was of the expected order of magnitude. At higher temperatures the crystals became intrinsic and no effect was observed in accordance with the fact that the ambipolar mobility is zero in the intrinsic region.

* Work supported by U. S. Signal Corps.
[1] B. Davydov and B. Gurevich, J. Phys. U.S.S.R. **7**, 138 (1943).

THURSDAY AFTERNOON AT 5:00

Quadrangle Club

Social Affair

FRIDAY MORNING AT 9:15

Eckhart 133

(L. APKER presiding)

Photoconductivity

J1. Theory of Trapping Model of Photoconductivity. RICHARD L. PETRITZ, *U. S. Naval Ordnance Laboratory.*—A development of the majority carrier model of photoconductivity was given[1] in which the role of the minority carrier was not explicitly considered. We have now developed the two carrier extension such that both majority and minority carriers, along with surface and bulk traps and recombination centers are considered explicitly. We find closed-form expres-

sions for the photoconductive response, generation-recombination noise, noise-equivalent power, and field effect response. A limiting form of interest in analyzing experimental data on lead sulfide films as will be given in the following paper is, $R_s = \Delta\sigma/4\sigma J = (1+B)\eta\beta\tau/4pdh\nu$ where all symbols except β are defined in our previous paper and also by Rose and Lampert.[2] The new parameter β is the ratio of minority carriers trapped to those which recombine rapidly with holes through recombination centers. The relation of β and τ to cross sections and densities of surface and bulk states will be discussed. In a previous paper,[3] retrapping of minority carriers, probably in surface states, is necessary to explain the long majority carrier lifetimes of PbS. Finally the equations of field-effect and noise will be presented and discussed briefly.

[1] R. L. Petritz, Phys. Rev. 104, 1508 (1956).
[2] A. Rose and M. A. Lampert, Bull. Am. Phys. Soc. Ser. II, 3, 114 (1958), following abstract.
[3] R. L. Petritz, Bull. Am. Phys. Soc. Ser. II, 1, 177 (1956).

J2. Investigation of the Sensitization of Lead Sulfide Photoconductive Films. FRANCES L. LUMMIS, D. E. BRAYTON, R. F. BRÜBRICK, E. GUBNER, AND R. L. PETRITZ, *U. S. Naval Ordnance Laboratory.*—We have prepared photoconductive films of lead sulfide by using a wide range of chemical deposition conditions. The responsivity R_s, noise, noise-equivalent-power, resistance R, Hall-coefficient R_H, thickness d, and time constant τ, are measured on all films. From these measurements we calculate resistivity ρ, carrier density p, and Hall mobility μ_H. The responsivity varies over a factor of 10^3. Time constants vary from 500 μsec to less than 1 μsec. The resistivity varies from 1 to 100 ohm cm; carrier density from 10^{16} to 10^{18} carriers/cm^3; thickness from 0.1 to 1 μ; and Hall mobility from 1 to 10 cm^2/v sec. Correlations between responsivity and the various physical parameters are being investigated. A definite correlation between R_s and τ has been established. The data are being interpreted in terms of the trapping model of photoconductivity discussed in the previous paper.[1] We calculate the quantum efficiency η from absorption and reflectivity data and the measured film thickness. This, along with measured values of R_s, τ, p, d, and $B=0$, allow us to calculate β, the efficiency of trapping. Our results indicate that β varies with initial chemical composition.

[1] R. L. Petritz, Bull. Am. Phys. Soc. Ser. II, 3, 114 (1958), preceding abstract.

J3. Gain-Band-Width Product for Photoconductors. A. ROSE AND M. A. LAMPERT, *RCA Laboratories.*—The gain-band-width product for a photoconductor can be written $G/\tau_0 = M/\tau_r$. G is the ratio of photoelectron current to photon current, τ_0 the photoresponse time, and τ_r the ohmic relaxation time. Both times are evaluated under illumination. $M = N_A N/N_T(N+N_D)$. N_A is the total number of positive charges on the anode due to the applied voltage. N_D and N are the total number of free electrons in the dark, and excited by the light, respectively. If the response time is not controlled by the contacts,[1] then N_T is generally the total number of electrons, trapped plus free, excited by the light and effectively in thermal equilibrium with the conduction band. In a wide variety of cases, and for voltages just sufficient to produce space-charge-limited currents, M is expected to be unity.[2]

[1] M. A. Lampert and A. Rose, Bull. Am. Phys. Soc. Ser. II, 3, 114 (1958), following abstract.
[2] A. Rose, Helv. Phys. Acta 30, 242 (1957).

J4. Contact-Controlled Photoconductive Response Time. M. A. LAMPERT AND A. ROSE, *RCA Laboratories.*—A change in current through a semiconductor or insulator requires a redistribution of the charge in the neighborhood of the injecting contact. The time it takes to effect this redistribution can be the factor controlling the photoconductive rise-time τ_0. Here τ_0 is defined as the time elapsed before the current doubles, at fixed voltage, after the incident light intensity has been doubled. In this case τ_0 becomes the time it takes for the action of the light to shift the potential minimum at the injecting contact a distance of approximately one Debye length Λ toward the contact interface. $\Lambda = (\epsilon kT/e^2 n_T)^{\frac{1}{2}}$ in mks units, with n_T the total density of excess carriers, free plus trapped, at the potential minimum, the other symbols being standard. Under these conditions, referring to the companion paper,[1] in the gain-band-width formula $M \simeq N/N_T$ with N_T now given by $n_T A\Lambda$, with A the cross-sectional area. For a phototransistor with a sufficiently narrow base region, "contact" (junction) space-charge will, in like manner, determine the response time and hence, the gain-band-width product.

[1] A. Rose and M. A. Lampert, Bull. Am. Phys. Soc. Ser. II, 3, 114 (1958), following abstract.

J5. Heating Effects Accompanying Photoconductivity and the Photoelectromagnetic Effect in Semiconductors.* I. I. SOCHARD AND J. H. BECKER, *National Bureau of Standards.*—A well-known method for determination of lifetimes of electron-hole pairs in semiconductors uses photoconductivity and photoelectromagnetic (PEM) short-circuit current measurements. Sample heating always occurs and produces "bolometer" action and "thermoelectromagnetic" effects (diffusion of thermally excited carriers in a magnetic field). These can seriously hinder evaluation of the lifetimes, especially for intrinsic materials with small ambipolar diffusion lengths $[L = (D\tau)^{\frac{1}{2}}]$. When the heating phenomena are dominant the thermal diffusivity can be estimated. In lifetime measurements it is customary to modulate the incident radiation at audio-frequencies. Increasing this "chopping" frequency f decreases the thermal signals (for "thick samples," Bol$\sim f^{-1}$, TEM$\sim f^{-\frac{1}{2}}$) which facilitates lifetime measurements; for a lifetime determination in Mg_2Sn [1] $f \gg 10^4$ cps is required above room temperature. Data at chopping frequencies between 20 and 13 000 cps will be shown for intrinsic and extrinsic samples of Mg_2Sn. Analysis will include an estimate of the minimum lifetimes determinable by the PC-PEM method in terms of the chopping frequency and known electrical and thermal properties of a semiconductor.

* Research supported by the Office of Scientific Research, Air Research and Development Command, U. S. Air Force.
[1] I. I. Sochard and J. H. Becker, Bull. Am. Phys. Soc. Ser. II, 2, 210 (1957).

J6. Photoconductivity in Semiconducting Diamond.* C. CURTIS JOHNSON AND WILLIAM J. LEIVO, *Oklahoma State University.*—Studies have been made of the photoconductivity in semiconducting diamond as a function of the wavelength, temperature, electric field strength, intensity of incident radiation, and crystal orientation. At room temperature the region of photoconductivity is broad, extending from 0.375 to 2.1 μ with the maximum at 0.6 μ. Peaks also occur at 0.224 and 0.228 μ. At lower temperatures various peaks in photoconductivity can be resolved. Maxima in photoconductivity at 152°K occur at 0.52, 0.92, 1.24, 1.64, and 2.16 μ. The maxima in photoconductivity shift to shorter wavelengths and decrease in magnitude with decreasing temperature. Above room temperature the photoconductivity increases with increasing temperature to approximately 400°K after which it commences to decrease. The photoconductivity is linear with respect to electric field strength, and it is also linear with respect to the intensity of the incident radiation. A good signal-to-noise ratio can be obtained. The photoconductivity has a slight directional dependence. Conducting diamonds were first discovered by J. F. H. Custers, and we thank him for furnishing the specimens used in these studies.

* Research supported by the U. S. Air Force through the Office of Scientific Research of the Air Research and Development Command.

J7. Complex Surface Photoconductivity of Ge in Visible and Ultraviolet.* R. W. CUNNINGHAM AND RALPH BRAY, *Purdue University.*—Au-doped Ge (high resistivity, p type at 85°K) has been used for sensitive detection of surface photoeffects. White light produces a very slowly decaying, highly conducting, accumulation layer.[1] The details of the spectral dependence have been investigated in range 0.25 to 1.4 μ. Generally, four regions of interest appear, the most characteristic being a large, but slow, buildup of conductivity starting $\sim$0.45 μ and peaking at $\sim$0.37 μ. A small buildup appears at longer wavelengths, peaking near 0.6 μ and showing relatively fast decay (order of minutes). The decay at shorter wavelength contains this fast component and also a much slower one. This suggests that trapping of electrons in inner and outer surface states give the fast and slow effects, respectively. The short wavelength threshold may be attributed to an oxide barrier which restricts passage of electrons from bulk Ge to outer states. The decay of these fast and slow components can be accelerated by irradiation at $\sim$0.5 μ and $\leq$0.31 μ, respectively. The appearance of these "negative" effects is dependent on the particular chemical etch and may relate to absorption of light in oxide layer or surface states directly.

* Work supported by Signal Corps contract.
[1] R. W. Cunningham and R. Bray, Bull. Am. Phys. Soc. Ser. II, 2, 348 (1957).

J8. Extrinsic Photoconductivity in Copper-Doped Indium Antimonide.* R. F. BLUNT, *National Bureau of Standards.*—n-type InSb was doped with copper to give both n- and p-type material with carrier concentrations ranging from 1×10^{14} to 5×10^{15} cm^{-3}. Impurity photoconductivity was observed out to at least 36 μ in the p-type material at 5°K with a number of maxima in the 6- to 20-μ region and showed a small dip corresponding to the lattice band at 28 μ. Absorption bands at 21.5 μ and perhaps at 16 μ were observed below 85°K suggesting optical transitions involving impurity levels. Hall coefficient measurements below 78°K give an impurity de-ionization slope of 0.027–0.055 ev (depending on the degree of compensation), followed at lower temperatures by impurity conduction. The conductivity decreases several orders of magnitude below 78°K, flattening off to less than 10^{-3} ohm^{-1} cm^{-1} below 20°K. The observed extrinsic photoconductivity is thus probably due to deep-lying acceptor levels. The n-type material exhibits negative impurity photoconductivity at 5°K (with a definite cutoff at about 21 μ) which suggests a "quenching" process where the quenching radiation is chopped monochromatic extrinsic radiation and the normal "quenched" photoconductivity arises from unchopped room-temperature radiation. The addition of extra unchopped intrinsic radiation definitely increases the negative photoconductivity in support of this view.

* Research supported by Office of Naval Research.

J9. Average Ionization Energy from Gamma Rays in Photoconductive CdS. E. H. TOMPKINS AND R. J. ROBINSON, *Armour Research Foundation.*—An approximate bulk ionization energy, 6±1 ev, has been measured in CdS from a correlation of visible light and gamma-ray induced photoconductivity. A modified gain term, gain_γ, for gamma-ray induced photoconductivity was employed following Rose's phenomenological theory of photoconductivity. The absorption coefficient for the Co^{60} and Cs^{137} gamma radiation is so small that a uniform generation of carriers throughout the bulk could be assumed. For the visible light gain term, gain_{vis}, a 20-A band was used at the peak of the photocurrent response. While the absorption in this region is principally a bulk absorption, i.e., nonsurface absorption, it is not, of course, uniform. In order, therefore, to minimize the diffusion terms in the current density expression, the light was directed on the crystal perpendicular to the direction of the applied electric field and bathed the whole sample. The crystals chosen for the data to be discussed had flat and nearly parallel faces, and showed no striations or other visible imperfections.

J10. Recent Observations on the Bulk and Dember Photovoltaic Effect in CdS. R. J. ROBINSON, *Armour Research Foundation.*—Some recent photovoltaic experiments on single crystals of photoconductive CdS using melted indium electrodes are discussed. The experiments to be described include (a) the investigation of the bulk photovoltaic effect in CdS using a small light spot, (b) the discussion of a new, apparently, bulk photovoltaic effect—the reversal in the direction of the photo emf with change in wavelength of the exciting radiation, (c) the investigation of the bulk photovoltaic effect using x-ray radiation from a microfocus x-ray tube. In this last experiment the Guinier-Tennevin technique for studying imperfections using a focused Laue spot method has been combined with an x-ray induced bulk photovoltaic effect as a means for studying the contribution of inhomogeneities in crystal space to the inhomogeneities in energy space. Two other studies are briefly discussed: the quenching of the photovoltaic effect in CdS with heat, and the use of the Dember effect to study replenishing electrodes in photoconductivity. The results of applying Tauc's[1] basic equations and the use of the Onsager relations will be briefly discussed.

[1] Jan Tauc, Revs. Modern Phys. 29, 308 (1957).

J11. Electric Field Action on Slurry CdS Photoconductors. A. BRAMLEY, *DuMont Laboratories.*—Two different sets of quenching experiments are reported on slurry CdS films (fine CdS particles embedded in 2% ethyl cellulose). One deals with the action of strong ($\sim$20 kv/cm) fields perpendicular to the photoconductor surface, the other with illumination by a brief ($\sim$10 μsec) intense light pulse. (1) Under the action of perpendicular strong ac fields slurry photoconductors behave similarly to evaporated ones.[1] Application and grounding of a strong dc field positive along the inward normal to the photoconductor surface (external electrode negative) results at moderate light levels in a marked decrease in photocurrent followed by slow recovery. (2) A dc potential, below the breakdown potential of the photoconductor in the dark, is applied across the photoconductor in series with a high resistance ($\sim$1 megohm). A transient current pulse, of about the same duration as the light pulse and followed by normal decay, is observed when the photoconductor is illuminated with a strong light pulse ($\sim10^4$ ft-cd). The maximum current measured on the grounded side of the photoconductor is many times the steady-state current, which would flow if the photoconductor were shorted.

[1] A. Bramley, Bull. Am. Phys. Soc. Ser. II, 1, 286 (1956).

J12. Preparation and Properties of Photoconducting Zinc Selenide Crystals. EDWARD L. LIND AND RICHARD H. BUBE, *RCA Laboratories.*—Photosensitive crystals of ZnSe have been prepared from the vapor phase with incorporated Group VII donors and/or Group I or Group V acceptors. Crystals of ZnSe:Br:Cu and ZnSe:Br:Sb have a sensitivity approaching that of photosensitive CdSe:I:Cu crystals. The spectral response of ZnSe:Br:Cu and ZnSe:Br:Ag crystals consists of a peak near the 4650-A absorption edge of ZnSe, plus additional long-wavelength impurity response cutting off at 6000 A. ZnSe:Br:Sb and ZnSe:Br:As crystals show in addition a long-wavelength tail out to 14 000 A. Br enhances crystal growth, and the incorporation of Br is accompanied by a change in the color of the crystals from light yellow to orange. Sb or As inhibit crystal growth, and the incorporation of such Group V impurities alone results in crystals with high resistivity and almost negligible photosensitivity. X-ray

analysis of the crystals reveals that most have both cubic and hexagonal regions. Saturation of photocurrent with voltage occurs frequently in photosensitive ZnSe crystals; an oscillating photocurrent was observed, in a region of saturated photocurrent at low temperatures, with a period decreasing from 34 to 1.5 sec with increasing light intensity, even though a dc field was applied and excitation was by steady illumination.

J13. Impurity Levels in Photoconducting Zinc Selenide Crystals. RICHARD H. BUBE AND EDWARD L. LIND, *RCA Laboratories*.—Impurity levels for Group VII donors, Group I acceptors, and Group V acceptors in ZnSe have been determined by measurements of conductivity *vs* temperature, photoconductivity *vs* temperature, spectral response, and infrared quenching. Br donors in ZnSe have an ionization energy of 0.21 ev, a value close to that found for Cl in ZnS. Cu and Ag acceptors have an ionization energy of 0.6 ev, approximately the same as these same acceptors in CdSe, even though the band gap of ZnSe is 55% larger than that of CdSe. Sb and As acceptors have two levels with ionization energies of 0.7 ev and 1.3 ev; the double levels found with Group V acceptors are very like those found in annealing-sensitized CdSe: levels lying 0.6 and 1.0 ev above the top of the valence band are tentatively associated in CdSe with multiple ionization of cation vacancies. The similarity of donor energies between ZnS and ZnSe, and of acceptor energies between ZnSe and CdSe, may be viewed as part of a more general correlation of donor and acceptor energies of Group II to Group VI compounds. It appears that the donor energies are determined primarily by the cation, whereas the acceptor energies are determined primarily by the anion.

FRIDAY MORNING AT 9:15

Pathology 117

(G. J. DIENES presiding)

Irradiation Effects, I

JA1. Small Angle Scattering as a Tool in Radiation Damage Studies. R. H. BRAGG, *Armour Research Foundation*.—Radiation damage in some materials can be characterized by small angle x-ray scattering. Recent experiments on neutron irradiated LiF[1,2] show a pronounced small angle scattering. Analysis of the published data indicates that the mean size, shape, and composition of the damaged regions can be deduced. The small angle scattering technique appears applicable to other systems if sufficient displacements can be produced, but defect concentrations lower than 10^{-4} probably cannot be detected. In neutron irradiated LiF the damaged regions are elongated ellipsoids or rods at low doses, but as saturation is reached these regions are converted to flattened ellipsoids or plates. Further irradiation does not affect the mean size or shape appreciably, but annealing produces a more equant shape. Criteria for the observation of small angle scattering will be discussed and experiments leading to more precise information will be proposed. It appears that some refinements in small angle scattering theory may also be necessary.

[1] M. Lambert and A. Guinier, Compt. rend. **244**, 2791 (1957).
[2] R. E. Smallman and B. T. M. Willis, Phil. Mag. **2**, 1018 (1957).

JA2. Effect of Proton Irradiation on the Catalytic Activity of Copper.* C. C. ROBERTS, AIJA SPILNERS, AND R. SMOLUCHOWSKI, *Carnegie Institute of Technology*.—An influence of high-energy proton irradiation on electrode potential, on solubility, and on reduction of various solids has been observed previously. The present investigation is an attempt to study similar effects in a well-known catalytic reaction: the decomposition of formic acid into carbon dioxide and hydrogen in the presence of metallic copper and the ensuing rise in pressure. The reaction, which is of zeroth order, was studied isothermally in the temperature range from 150 to 185°C and the rate constants and the activation energies were determined. The sample was in form of a sheet of an area of 100 to 200 cm sq. It appears that an irradiation with a 350-Mev proton flux of the order of 10^{15} lowers the activation energy from about 25 kcal to half this value. Upon annealing at about 175°C the metallic surface seems to recover its original property and the rate constants and activation energies return to values characteristic of the nonirradiated material. The probable mechanism of these phenomena will be discussed.

* Work supported by a U. S. Atomic Energy Commission contract.

JA3. Radiation Induced Color Centers in Al_2O_3.* PAUL W. LEVY, *Brookhaven National Laboratory*.—Gross features of the radiation induced coloring of crystalline Al_2O_3 were previously reported.[1] The resolution of numerous spectra into component bands gives the following results: In unirradiated crystals bands are found at 6.1, 5.4, and 4.7 ev. The peak energy and full width, in ev, of the strongest gamma-ray induced bands are: 5.45.4 (1.25), 4.80 (0.9), 3.08 (1.5), and possibly one at 4.28 (0.7). The strong reactor induced bands are 6.04 (0.6), 5.34 (0.4), 4.84 (0.54), 4.21 (0.8), 3.54 (0.5), and possibly weak bands at 2.95 (0.66), 2.42 (0.5). However, there may be a reactor induced band at 5.8, and if so, the band given as 5.34 (0.4) occurs at 5.54 (0.6). This uncertainty, as well as errors in peak energy (approximately 0.1 ev) and full width, arise from uncertainties in the resolutions. Occasionally the widths may be in error by a factor of two. Sufficient heating will remove all of the induced coloring and diminish that found in unirradiated crystals. Also, quenching Al_2O_3 crystals from near their melting point before irradiation increases the amount they are colored by gamma rays.

* This work performed under the auspices of the U. S. Atomic Energy Commission.
[1] P. W. Levy and G. J. Dienes, *Bristol Conference on Defects in Crystalline Solids* (The Physical Society, London, 1955).

JA4. Gamma-Ray Induced Coloring of Potassium Azide.* J. E. MAPES† AND R. W. DREYFUS,‡ *Picatinny Arsenal*, AND PAUL W. LEVY, *Brookhaven National Laboratory*.—Single crystals of potassium azide (KN_3) have been colored by Co^{60} gamma rays in successive doses totaling 1.7×10^{6} r and their absorption spectra determined from 5 to 0.5 ev (0.25 to 2.5 μ). Both irradiation and measurement were performed at room temperature. Unirradiated crystals show no absorption bands except that the apparent absorption edge may be a band. The induced bands increase in intensity with exposure, and their maxima occur at 3.5 ev (355 mμ), 2.1 ev (590 mμ), and 1.5 ev (830 mμ). The latter two bands decay with time. The exact shape of the 3.5-ev band is obscured by the apparent absorp-

tion edge of the crystal, but the remaining spectrum has been separated into component bands by utilizing the difference in decay rates and assuming the bands have Gaussian shape. For some of the bands this assumption is surprisingly good. The band at about 1.5 ev has both a slowly decaying component with full width of 0.9 to 1.0 ev, and a rapidly decaying component with a width of 0.6 ev. Another rapidly decaying band occurs at 2.1 ev, with a width of 0.6 to 0.75 ev.

* Supported jointly by Picatinny Arsenal and the U. S. Atomic Energy Commission.
† Guest Scientist, Brookhaven National Laboratory.
‡ Now at Yale University.

JA5. Neutron and Gamma Irradiation of Lead and Potassium Azide.* J. K. RANEY, *Armour Research Foundation.*—Lead and potassium azide have been investigated for decomposition and/or structural changes with gamma and/or neutron irradiation. Neutrons were supplied by the Armour Research Reactor and gamma irradiation was performed with a Co^{60} source. When single crystals of lead azide are neutron irradiated, they undergo a conversion to lead carbonate. With the aid of x-ray powder diffraction patterns, a mechanism for the decomposition has been postulated. A total dose of approximately 7.5×10^{16} n/cm² has been found to be sufficient for this conversion. Gamma-irradiation effects in potassium azide have been observed for a dose of 7×10^{8} r. The presence of free electrons has been observed by electron paramagnetic resonance absorption measurements giving evidence of color center formation of the *F*-center type.

* This program has been supported by ERDL.

JA6. (Abstract withdrawn.)

JA7. Effects of Nuclear Environment on Magnetic Material. (A) 60-cy Characteristics of Ferrites. E. I. SALKOVITZ, A. I. SCHINDLER, AND G. S. ANSELL, *U. S. Naval Research Laboratory.*—A variety of commercially available ferrites were irradiated in the Brookhaven graphite reactor for a total integrated flux of 10^{17} nvt (fast). During the irradiation the temperature was kept relatively constant by air cooling. Most of the samples were magnetically "soft" and in the form of toroids. On the toroids were wound the appropriate primary and secondary coils in order to obtain hysteresis loops at 60 cy with a B-H loop tracer[1] in the hot cell facilities at the U. S. Naval Research Laboratory before and after irradiation. From the hysteresis loops the effect of the irradiation on the flux density, coercive force, remanence, and losses could readily be obtained. In general, magnesium-manganese ferrites showed no significant changes, whereas the nickel-zinc ferrites showed effects on the above parameters. In addition to these ferrites, several magnetically "hard" ferrites were examined in a very qualitative manner. Using a Hall effect probe-type gaussmeter the field on the surface of lead and barium ferrites was measured before and after irradiation. The lead ferrites showed a 15% decrease, the barium ferrite from one source showed no decrease, while that from another source showed a 12% decrease.

[1] William A. Geyger, Proc. Natl. Electronics Conf. (1956), Vol. 12.

JA8. Effect of Nuclear Environment on Magnetic Materials. (B) 60-cy and dc Characteristics of Alloys. A. I. SCHINDLER, E. I. SALKOVITZ, AND G. S. ANSELL, *U. S. Naval Research Laboratory.*—As part of the irradiation program mentioned previously,[1] nine torroid samples of various ferromagnetic alloys, including low loss material, high permeability material, square loop material, and ordered alloys were irradiated. Some of these materials correspond to those studied previously and concurrently by Sery, Fischell, and Gordon.[2] The results on the duplicated studies are in agreement with their work. As in the previous abstract, hysteresis loops were made at 60 cy, and in some cases dc hysteresis loops were made as well. No changes resulting from an irradiation of 10^{17} nvt (fast) were found either for a cold-rolled 3% silicon iron sample, or for an ordered aluminum Heusler alloy. Large changes, including increases in coercive force and decreases in remanence and maximum flux density were found for the remainder of the samples. In addition, after irradiation certain samples also exhibited new structure in the hysteresis loops. The materials demonstrating this behavior were characterized by being basically iron-nickel alloys.

[1] Salkovitz, Schindler, and Ansell, Bull. Am. Phys. Soc. Ser. II, 3, 117 (1958), preceding abstract.
[2] Sery, Fischell, and Gordon, *Conference on Magnetism and Magnetic Materials, October, 1956* (American Institute of Electrical Engineers, February, 1957).

JA9. Nuclear Irradiation Effects on Soft Magnetic Materials. R. S. SERY AND D. I. GORDON, *U. S. Naval Ordnance Laboratory.*—Nuclear irradiation causes appreciable changes in the properties of soft magnetic materials. Current and previous[1,2] experiments utilizing the BNL reactor ($\sim10^{12}$ nv for 10^{18} nvt) show: (1) Structure sensitive properties (permeability, coercive force, remanence) showed large changes. Saturation induction, a structure-insensitive property, changed but negligibly. (2) Because of the correlation between structure sensitive magnetic properties and order-disorder, one may conclude that the radiation induced changes in magnetic properties reflect changes in degree of order. (3) Materials with high initial permeability and low coercive force (Supermalloy, 4–79 Mo Permalloy, mumetal, 50–50 nickel-iron) are most affected. The initial and maximum permeabilities of Supermalloy decreased 93% and its coercive force increased eightfold. (4) Materials of relatively low initial permeability and higher coercive forces showed little or no change (16 aluminum-iron, silicon-irons, and silicon-aluminum-iron). (5) Magnetic data taken periodically during irradiation showed progressive changes in properties with increasing nvt. Some materials showed saturation of radiation damage effects. (6) Reannealing restored the preirradiation switching time

characteristic of 4–79 Mo Permalloy (½-mil tape) after irradiation had destroyed this property, indicating that transmutation-induced changes in magnetic properties are negligible.

[1] Sery, Fischell, and Gordon, *Conference on Magnetism and Magnetic Materials, October, 1956* (American Institute of Electrical Engineers, February, 1957).
[2] Gordon, Sery, and Fischell, Nucleonics (to be published).

JA10. Effect of Neutron Irradiation on Martensite Transformation in Iron-Nickel Alloys.* LEW F. PORTER† AND G. J. DIENES, *Brookhaven National Laboratory.*—Wire specimens of iron-25.5 atomic percent nickel alloy, heat-treated to produce 100% gamma phase, as well as various amounts of martensite were irradiated to a flux of 10^{17} nvt, epicadmium, in the Brookhaven reactor at a temperature of 50°C, slightly higher than the normal Ms temperature for the alloy. Electrical resistivity measurements were used to determine the course of the transformation. In agreement with the work of Reynolds, Low, and Sullivan[1] on stainless steel, it appears that a small amount of additional transformation is stimulated by the irradiation when martensite is present. However the Ms temperature of the alloys, determined after irradiation, is found to be lowered approximately 6°C by the damage produced. Neutron irradiation thus appears to have a dual effect in this case, promoting transformation during irradiation but inhibiting transformation subsequent to irradiation. Possible mechanisms to account for the observations will be discussed.

* Under contract with the U. S. Atomic Energy Commission.
† Guest Scientist at Brookhaven National Laboratory from U. S. Steel Corporation.
[1] Reynolds, Low, and Sullivan, J. Metals 7, 555 (1955).

JA11. Effect of Neutron Irradiation on Cu-Al Alloys. R. H. KERNOHAN AND M. S. WECHSLER, *Oak Ridge National Laboratory.**—In-pile electrical resistivity measurements at about 40°C on α solid solutions with 5.6, 9.6, and 14.8 atomic percent Al in Cu have been made, which show an initial decrease in resistivity followed by a gradual increase. These changes are interpreted as being due to the superposition of two effects: (1) process A, a linear increase due to bombardment-produced defects, and (2) process B, a saturating decrease due to a diffusion-controlled solid state reaction. The magnitude of the changes due to both processes increases with Al concentration. Process B saturates at a neutron exposure of about 10^{18} neutrons/cm^2 and, for the 14.8 atomic percent Al alloy, the decrease amounts to about 0.2 μohm cm. This decrease anneals out at temperatures in the range 150–250°C. Furthermore, process B does not occur upon irradiation at −120°C, but is observed in this case to set in upon subsequent annealing above 0°C. The activation energy for this annealing process is 1.0 ev.

* Oak Ridge National Laboratory is operated by the Union Carbide Corporation for the U. S. Atomic Energy Commission.

JA12. Effect of Quenching on Cu-Al Alloys. M. S. WECHSLER AND R. H. KERNOHAN, *Oak Ridge National Laboratory.**—Electrical resistivity measurements have been made under the following circumstances on unirradiated Cu−Al single crystals containing 14.8 atomic percent Al: (1) upon quenching into water from 200–520°C, (2) upon air-cooling from 200–520°C, and (3) at temperature in the range 25–650°C. The quenching experiments indicate that an excess resistivity is quenched-in which increases with the quenching temperature and reaches a maximum of about 0.5 μohm cm for T_Q=450°C. An excess resistivity is also retained upon air-cooling, which has a maximum of 0.2 μohm cm upon cooling from 310°C. The static measurements indicate that the defects retained upon quenching and air-cooling have an unusually low energy of formation (about 0.2 ev). Annealing experiments after quenching show that the quenched-in resistivity anneals out with about the same activation energy as for annealing after neutron irradiation at −120°C[1] although at somewhat higher temperatures. The effects upon quenching will be correlated with those upon neutron irradiation and possible explanations will be discussed.

* Oak Ridge National Laboratory is operated by the Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] R. H. Kernohan and M. S. Wechsler, Bull. Am. Phys. Soc. Ser. II, 3, 118 (1958), preceding abstract.

JA13. Theory of Irradiation Effects in Alloys. R. E. JAMISON, *Oak Ridge National Laboratory.**—To explain the retardation of zone growth in previously irradiated Al−Ag,[1] it is hypothesized that the range of an individual knock-on in an alloy is strongly dependent on its ionic radius. This results in a net flow of the small-ion element out of the region of the primary knock-on and its associated concentration of vacancies and large-on interstitials so that on room temperature bombardment there exist two rather isolated diffusion processes: a low required-energy recombination of close large-ion interstitial vacancy pairs and a high required-energy migration of small-ion interstitials to preirradiation vacancies or dislocations. There remains, of course, a random distribution of excess vacancy clusters. From theoretical considerations it can be argued that the ratio of the high-energy to the low-energy processes will be high except for the most dilute alloys, since the presence of even small amounts (0.1 atomic percent) of solute in the region of the primary knock-on will generally restrict the production of close interstitial vacancy pairs. The verification of these concepts will be discussed.

* Oak Ridge National Laboratory is operated by the Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] R. E. Jamison, Bull. Am. Phys. Soc. Ser. II, 2, 151 (1957).

JA14. Effect of Electron Irradiation on Cluster Formation in Al-2 Atomic Percent Cu Alloy. C. W. TUCKER, JR., AND H. N. TREAFTIS, *General Electric Research Laboratory.*—When an homogenized and quenched Al-2 atomic percent Cu alloy is held at relatively low temperatures[1] (−20° to +20°C) there are resistivity changes of a few percent indicating agglomeration of the copper atoms.[1] Experiments have been performed to determine the effect of irradiation with 1.5 Mev electrons on this process. Irradiation (7×10^{16} electrons/cm^2) at −145°C had no effect on the course of the resistance-time curves at −20°C. However, when the irradiations were performed at −60°C, at which temperature the agglomeration process will go very slowly thermally, irradiation has a large effect on the resistance-time curves at −20° and 0°C. It is shown that irradiation defects (which decay during the irradiation) promote the agglomeration reaction during the irradiation and thus remove a large portion of the resistance changes which occur in the first few minutes of the resistance-time curves in the absence of irradiation. The results are quite analogous to those found in ordering systems and are interpreted to mean that clusters of two or three copper atoms are formed during the irradiation.

[1] D. Turnbull and H. Treaftis, Bull. Am. Phys. Soc. Ser. II, 1, 334 (1956).

FRIDAY MORNING AT 9:15

Mandel Hall

(T. ALFREY, JR., presiding)

Joint Symposium of the Divisions of High Polymer and Solid State Physics

Some Physical Properties of Crystalline Solids

K1. Crystallinity of Polymers and Mechanical Behavior. H. F. MARK, *Polytechnic Institute of Brooklyn.* (30 min.)

K2. Creep in Crystalline Solids. J. WEERTMAN, *U. S. Naval Research Laboratory.* (30 min.)

K3. An Internal Friction Study of Some Copolymers from 4.2°K to the Crystalline Melting Point. N. G. MCCRUM, *E. I. du Pont de Nemours and Company.* (30 min.)

K4. Kinetics of Order-Disorder Transformations. G. VINEYARD, *Brookhaven National Laboratory.* (30 min.)

FRIDAY MORNING AT 9:15

Kent 107

(E. W. MONTROLL presiding)

DCP Symposium

Applications of Magnetic Resonance to Problems in Molecular Physics

L1. Exchange Effects in Magnetic Resonance of Free Radicals. S. WEISSMAN, *Washington University.* (40 min.)

L2. Structural Interpretation of Indirect Spin Spin Coupling in Molecules. DEAN KARPLUS, *University of Illinois.* (40 min.)

L3. Spin Density Matrices for Paramagnetic Molecules. H. M. MCCONNELL, *California Institute of Technology.* (40 min.)

Business Meeting of the Division of Solid-State Physics

FRIDAY MORNING AT 9:15

Social Sciences 122

(S. KOENIG presiding)

Semiconducting Compounds

LA1. Segregation Constants and Carrier Mobilities in InSb.* ALAN J. STRAUSS, *University of Chicago.*—The following segregation constants have been obtained from measurements of impurity distributions in crystals of InSb grown by the Czochralski method: Zn, 3.3; Cd, 0.26; Te, 0.54; Se, 0.17. The crystals were pulled from the melt in approximately the (111) direction at 0.75 in./hr and simultaneously rotated at 130 rpm. The concentrations of added impurities were large enough compared to those of residual impurities to permit their accurate evaluation from the Hall constants of the samples at 77°K. Hall mobilities for these and other essentially uncompensated samples will be presented as a function of impurity concentration and compared with mobilities calculated from the lattice scattering and the impurity scattering obtained from the Brooks-Herring theory. For *n*-type samples, the theoretical and experimental values are in rather good agreement for impurity concentrations below 3×10^{16} cm^{-3}; at higher concentrations, presumably because of degeneracy, the experimental values are systematically lower than the theoretical ones. For *p*-type samples, even at low concentrations the experimental values are significantly lower than the theoretical values calculated assuming a hole effective mass of $0.18m_0$, the cyclotron resonance value. Rather good agreement is obtained for $m^*=0.35m_0$. For concentrations above 3×10^{17} cm^{-3}, the experimental values are again systematically lower than the theoretical ones.

* This research was supported by the U. S. Air Force, through the Office of Scientific Research of the Air Research and Development Command.

LA2. Magnetoresistance in InSb.* R. T. BATE, R. K. WILLARDSON, AND A. C. BEER, *Battelle Memorial Institute.*—Transverse magnetoresistance of *n*- and *p*-type InSb was measured at magnetic fields between 20 and 20 000 gauss for fixed temperatures between 50°K and 300°K. The *n*-type InSb had carrier concentrations of 1×10^{14} cm^{-3}, and mobilities of 5×10^5 cm^2/v-sec at 50°K. Corresponding values for the *p*-type sample were 1×10^{15} cm^{-3} and 1×10^4 cm^2/v-sec. In all cases, $\Delta\rho/\rho$ varied as H^2 at low fields. At low temperatures and high fields, the resistivity of the *n*-type samples was proportional to H/T, the parameter occurring in expressions for longitudinal magnetoresistance in the quantum limit.[1] In no case did the resistivity saturate at high fields. The field

dependence of resistivity in n-type material was less complex than that reported by others[2] in less pure material, presumably because effects of degeneracy and magnetic field dependence of Fermi level were small. Results are correlated with data[3] on the magnetic field variation of Hall coefficient, and are discussed with regard to scattering processes, large field quantization effects, and band structural considerations.

* This research was supported by the U. S. Air Force, through the Office of Scientific Research of the Air Research and Development Command.
[1] P. N. Argyres and E. N. Adams, Phys. Rev. **104**, 900 (1956).
[2] H. P. R. Frederikse and W. R. Hosler, Phys. Rev. **108**, 1136 (1957).
[3] Bate, Willardson, and Beer, Bull. Am. Phys. Soc. Ser. II, **2**, 347 (1957).

LA3. Mobility and Activation Energy of Beta Silicon Carbide.* ROBERT G. POHL, *Armour Research Foundation.*—Resistivity and Hall effect measurements for a macrocrystal of β-SiC indicated n type conductivity with 10^{20} carriers/cm^3, and a room temperature Hall mobility of 32 ± 10 cm^2/volt-sec. No photoconductivity was observable. The resistivity was independent of temperature up to 220°C. The crystal was dark blue, single crystalline, and grew along the (1, 1, 1) axis. The crystal, only 0.1 mm in diameter and 0.5 mm in length, was supported with 17-mil Elgiloy wires whose ends had been prepared by drilling 6-mil holes 6 mil deep so as to receive the crystal—this provided sturdy mechanical support during subsequent operations of mounting resistivity and Hall probes. A fibrous whisker form of β-SiC was observed in the crystal growing reaction tube, with some whiskers 4 microns in diameter and 2 mm long. Resistivity *vs* temperature measurements of microcrystalline β-SiC over the range of 0°C to 500°C indicate an activation energy of about two electron volts.

* Supported by Air Force Cambridge Research Center.

LA4. Magnetic Susceptibility of InSb. R. BOWERS, *Westinghouse Research Laboratories.*—The magnetic susceptibility of n-type InSb has been measured between 300°K and 1.3°K for carrier densities (N) ranging from 1×10^{14} to 7×10^{18}/cc. For carrier densities in excess of 3×10^{17}, the total susceptibility of the specimens was independent of temperature. The carrier susceptibility in the degenerate limit has been derived from the data,[1] in order to examine its variation as the Fermi level is raised in the conduction band. Our interest in InSb arises from its nonparabolic conduction band. The Fermi level in the most highly doped specimen is 0.35 ev. The measured degenerate carrier susceptibility exhibited the following form when plotted against $N^{\frac{1}{3}}$: At $N\simeq10^{18}$/cc, it departs from a straight line representing the Landau-Peierls value with $m^*=0.013$, the mass at the band minimum. The observed susceptibility subsequently increases less rapidly with $N^{\frac{1}{3}}$, reaching a maximum value of 0.31×10^{-7}/g near 10^{18}/cc and then decreasing with increasing $N^{\frac{1}{3}}$. Over most of the range the observed susceptibility is somewhat larger than a theoretical value obtained from the Peierls' expression[2] using Kane's calculation of the shape of the conduction band.

[1] R. Bowers, Phys. Rev. **108**, 683 (1957).
[2] Equation (1.3) in T. Kjeldaas and W. Kohn, Phys. Rev. **105**, 806 (1957).

LA5. Carrier Recombination in p-Type InSb.* R. N. ZITTER, A. J. STRAUSS, AND A. E. ATTARD, *University of Chicago.*—The photoconductive (PC) and photoelectromagnetic (PEM) effects in p-type InSb have been studied in detail as functions of free hole concentration at 77°K, and for several concentrations photoconductivity has been investigated as a function of temperature between 77°K and 300°K. At 77°K, it is found that the PEM lifetime, τ_{PEM}, is approximately 2×10^{-10} sec, independent of hole concentration, while $\tau_{PC}\doteq(4\times10^{7})/p_0$ sec, where p_0 is expressed in cm^{-3}. The fact that τ_{PC} is greater than τ_{PEM} for sufficiently pure samples indicates that excess electrons are trapped in bound states in the forbidden gap,[1] with the ratio of trapped to free electrons equal to $(5\times10^{18})/p_0$. Electron trapping is also indicated by the results of quenching experiments with dc light. The data for temperatures below 200°K will be interpreted in terms of a Shockley-Read recombination mechanism; at higher temperatures, a direct interband recombination mechanism (probably of the Auger type) appears to predominate.[2]

* This research was supported by the U. S. Air Force, through the Office of Scientific Research of the Air Research and Development Command.
[1] A. Rose, *Photoconductivity Conference* (John Wiley and Sons, Inc., New York, 1956), p. 17.
[2] G. K. Wertheim, Phys. Rev. **104**, 662 (1956).

LA6. The Electrical Properties of p-Type Indium Arsenide. JACK R. DIXON, *U. S. Naval Ordnance Laboratory.*—Previous experimental work[1,2] on the electrical properties of p-type indium arsenide has shown that for carrier concentrations greater than approximately 10^{17}/cm^3, the temperature dependence of the Hall constant is normal, showing a single n to p-type reversal. However, it has been reported[2] that for polycrystalline p-type indium arsenide doped with zinc so as to have carrier concentrations less than 10^{17}/cm^3, the Hall constant-temperature relationship is anomalous, often exhibiting double reversals. We have repeated this work using single crystals of zinc-doped indium arsenide and have reproduced the original results. However, we have found that the anomalies can be removed by appropriate heat treatment of the material. This heat treatment will be described, and data will be presented pertaining to the electrical properties of p-type indium arsenide as a function of temperature before and after such heat treatment.

[1] Folberth, Madelung, and Weiss, Z. Naturforsch. **9a**, 954 (1954).
[2] O. G. Folberth and H. Weiss, Z. Naturforsch. **11a**, 510 (1956).

LA7. Evidence for a Linear Energy Term in the Valence Band of InAs. FRANK STERN, *U. S. Naval Ordnance Laboratory.*—We have extended an earlier analysis[1] of the optical absorption of p-type InAs, using the theory of Kane,[2] to the absorption spectra obtained by F. Matossi[3] for a series of temperatures. Satisfactory agreement between theory and experiment was obtained with a linear energy term. Although the large number of parameters complicates interpretation of the results, we estimate the energy difference between the top of the valence band and the center of the Brillouin zone to be 0.003 ± 0.003 ev, and the spin-orbit splitting to be 0.43 ± 0.03 ev. The density of states mass in the valence band is energy dependent, but has a broad minimum value of 0.45 ± 0.05 m. Extension of Kane's theory is needed before the high temperature absorption curves can be analyzed.

[1] F. Stern and R. M. Talley, Phys. Rev. **108**, 158 (1957).
[2] E. O. Kane, J. Phys. Chem. Solids **1**, 249 (1957).
[3] F. Matossi, Bull. Am. Phys. Soc. Ser. II, **3**, 15 (1958).

LA8. Magnetoresistance of Electrons in Indium Phosphide.* M. GLICKSMAN, *RCA Laboratories.*—Measurements of the magnetoresistance have been made on oriented crystals of InP cut from large grains, with electron concentrations above 1×10^{16} cm^{-3}. These results have been analyzed in terms of Seitz's coefficients[1] b, c, and d for the low-field magnetoresistance. The values of these parameters appear to satisfy the symmetry conditions[2] for a mobility with (100) symmetry in the Brillouin zone. The anisotropy of the mobility is small with a value of about 1.3 for the ratio of transverse to longitudinal components in the (100) directions. If the symmetry of the mobility can be assumed representative of the effective mass anisotropy, these results suggest that the conduction band minima are either along the (100) axes in the Brillouin zone, or at the corner points W of the square face of the zone.[3]

* This work was supported in part by the U. S. Air Force.
[1] G. L. Pearson and H. Suhl, Phys. Rev. **83**, 768 (1951).
[2] B. Abeles and S. Meiboom, Phys. Rev. **95**, 31 (1954); M. Shibuya, Phys. Rev. **95**, 1385 (1954).
[3] R. H. Parmenter, Phys. Rev. **100**, 573 (1955); G. Dresselhaus, Phys. Rev. **100**, 580 (1955).

LA9. Effect of Pressure on Intrinsic Optical Absorption in Indium Arsenide and Gallium Antimonide.* J. H. TAYLOR, *Morgan State College.*—Measurements of the shift of the fundamental absorption edge with hydrostatic pressure have been made for the intermetallic compounds InAs and GaSb. In both materials the energy gap increases with pressure over the pressure range 1 to 2000 atmospheres. This experiment yielded values for the pressure coefficient which are larger than those deduced from conductivity measurements. For InAs and GaSb the pressure coefficients were found to be $8.5(10)^{-6}$ and $1.57(10)^{-5}$ ev/atmos, respectively.

* Supported by the Office of Ordnance Research.

LA10. Infrared Absorption in Gallium Antimonide.* A. K. RAMDAS AND H. Y. FAN, *Purdue University.*—*n*-type gallium antimonide shows typical free carrier absorption which increases smoothly with wavelength. In *p*-type samples the absorption increases rapidly up to $\sim 10\,\mu$, beyond which it remains substantially constant. The absorption at the long wavelengths increases with decreasing temperatures down to 90°K. These features suggest transitions between overlapping valence bands. Effective masses have been determined from the reflectivity, following Spitzer and Fan, giving 0.04 m for electrons and 0.44 m for holes. The absorption edge above 100 cm^{-1} has a shape similar to that of InSb and may be attributed to direct transitions. The tail observed below 100 cm^{-1} is more pronounced at 300°K than at 90°K, and a highly compensated *p*-type sample of large impurity concentration showed stronger absorption in this range. These observations are indicative of indirect transitions. Magnetoresistance of oriented *n*- and *p*-type specimens showed no longitudinal or anisotropy effects; however, this could be the case even for a many-valley band if energy surfaces in the individual valleys are approximately spherical. The absorption edge in impure *n*-type specimens shows the effect of high Fermi level, but the shape of the shifted edge is not as simple to interpret as the InSb and InAs.

* Work supported by a Signal Corps contract.

LA11. Anisotropic Hall Effect and Magnetoresistance in *n*-Type Bismuth Telluride. R. WOLFE,* R. D. GROVES, AND J. R. DRABBLE, *General Electric Company, England* (introduced by K. G. McKay).—The resistivity, Hall coefficients, and low field magnetoresistance coefficients associated with current flow in the cleavage planes have been measured at 77°K on a number of *n*-type single crystal specimens of bismuth telluride. The resistivity and Hall coefficient measurements were extended up to room temperature. The experimental results are shown to be reasonably consistent with a many-valley model[1] of the band structure in which the energy minima are situated on the reflection planes in *k*-space. The parameters associated with this model are evaluated and used to relate the two Hall coefficients to the density of carriers. These relations are used to obtain the conductivity mobility of electrons for current flow in the cleavage planes. This mobility varies as $T^{-1.48}$ over the temperature range 150°K to 300°K and has a value of 1250 cm/sec/volt/cm at room temperature.

* Present address: Bell Telephone Laboratories.

[1] J. R. Drabble and R. Wolfe, Proc. Phys. Soc. (London) **B69**, 1101 (1956).

LA12. Magnetoresistance Coefficients for Degenerate Statistics. R. S. ALLGAIER, *U. S. Naval Ordnance Laboratory.*—In an attempt to explain the large values of M_L/M_T, the ratio of longitudinal to transverse magnetoresistance, occurring in PbTe, M_L and M_T have been derived for degenerate statistics for the three cubic models treated by Abeles and Meiboom and by Shibuya. The results for several configurations of sample current and magnetic field will be presented as a function of K, the ratio of longitudinal to transverse effective mass. Previously reported experimental values of M_L/M_T obtained with the sample current parallel to a cubic axis, were as high as 4 or 5.[1] These values were measured at 4.2°K, where the samples were highly degenerate. For this configuration, the highest theoretical ratio for any of the three models and for any K is 2.43, using classical statistics and the scattering law $\tau = l/E^{\frac{1}{2}}$. For degenerate statistics and for τ equal to any function of E, the maximum ratio is 2. Thus it appears that other models must be sought to explain the magnetoresistance data in PbTe, or that anomalously large values of longitudinal magnetoresistance (possibly due to inhomogeneities) are occurring.

[1] R. S. Allgaier, Bull. Am. Phys. Soc. Ser. II, 2, 141 (1957).

Invited Paper

LA13. Polar Properties, the Chemical Bond, and Energy Bands in Zinc Sulfide. J. L. BIRMAN, *Sylvania Physics Laboratory.* (30 min.)

FRIDAY MORNING AT 9:45

Cobb 110

(A. W. LAWSON presiding)

Metals I. Mechanical Properties

M1. Fracture Rates in Solids. H. L. SMITH AND J. A. KIES, *U. S. Naval Research Laboratory.*—The driving force necessary to make a crack propagate has been investigated as a function of the crack length and the crack velocity in aluminum 2024T3 and 7075T6 alloys. Analysis of data for fatigue and for single loading tests shows that in general, the driving force is an increasing function of both variables over a wide range for velocities less than the limiting velocity for fracture. For materials more strain rate sensitive than the aluminum alloys, the fracture tends to become more brittle as the crack velocity increases. This was shown for a polyethylene material.

M2. Influence of Dislocation Motion on the Elastic Constants of the Face-Centered-Cubic Metals. G. DEWIT AND J. S. KOEHLER,* *University of Illinois.*—The dislocation contribution to the Young's modulus and the modulus of rigidity of circular rods of face-centered metals are calculated. It is shown that for well-annealed pure single crystals each of the three elastic constants will be lowered by several percent. The displacement of a pinned down dislocation under the action of a shearing stress is calculated noting that the line tension varies with orientation as follows:

$$E = K_1 - K_2 \cos 2\varphi,$$

where φ is the angle between the Burger's vector and the dislocation axis. K_2/K_1 increases as the elastic anisotropy increases. If $3K_2>K_1$ an edge dislocation is unstabile and the dislocation does not run straight between the end points even when no stress is applied. Lead approaches such instability. The influence of the dislocation core has not been treated.

* Work partially supported by the Office of Naval Research.

M3. Decay of Quenched-In Vacancies in Noble Metals. H. KIMURA, R. MADDIN, AND D. KUHLMANN-WILSDORF, *University of Pennsylvania.*—Two types of decay of quenched-in vacancies are considered. One type is due to the migration of vacancies toward the dislocation network; this type results in an exponential decay. The other type is due to the formation and growth of sessile dislocation rings by absorption of vacancies; the decay curve for vacancies to form sessile rings has been calculated as

$$N = N_0 \cosh^{-2}\left[\alpha e^{-E_M/kT}\frac{\pi}{2}(N_0 N_s)^{\frac{1}{2}}t\right],$$

where N_0 and N are the number of vacancies at the beginning of the annealing and time t, respectively; α is a constant, E_M is the activation energy for migration of vacancies, and N_s is the number of sessile rings. When the number of quenched-in vacancies is large, some meet each other to form sessile rings, while others migrate to the dislocation network. When the number is small, the vacancies migrate mainly to the network. Bauerle and Koehler's research[1] on the quenched-in resistivity in Au shows these two types of decay and is explained by the present theory.

[1] J. E. Bauerle and J. S. Koehler, Technical Report No. 8, DA-11-022-ORD-1212, Office of Ordnance Research.

M4. Magnetic Field and Temperature Dependence of Ultrasonic Attenuation in Bismuth. DARRELL H. RENEKER,* *University of Chicago* (introduced by A. W. Lawson).—Measurements of ultrasonic attenuation in the frequency range of 12 to 60 Mc at temperatures from 1.2 to 300°K and fields up to 1000 oe on zone refined bismuth crystals are in progress. Preliminary measurements show that at helium temperatures the attenuation as a function of $1/H$ has an oscillatory component superimposed on a monotonically decreasing component the magnitude of which is approximately proportional to the frequency for fixed H. In addition there is a field-independent attenuation of the same magnitude which varies with temperature and is presently ascribed to crystalline imperfections. The period of the oscillatory component is proportional to the sound wavelength. The preliminary results appear to be consistent with Pippard's[1] theory and therefore it is hoped that information relating directly to the shape of the Fermi surface will be obtained.

* Predoctoral National Science Foundation Fellow.
[1] A. B. Pippard, Phil. Mag. 2, 1147 (1957).

M5. Anisotropy of the Zener Relaxation in Body-Centered-Cubic Alloys.* D. P. SERAPHIM AND A. S. NOWICK, *IBM.*—The dependence of the magnitude of the internal friction peak in substitutional solid solutions on crystal orientation, which was previously[1] investigated for f.c.c. crystals, is now studied in the case of b.c.c. single crystals. Theoretical treatments,[2,3] based only on nearest neighbor interactions, predict that the relaxation strength, Δ_E, is zero for ⟨100⟩ oriented b.c.c. crystals. The experiments of Artman[4] on beta-brass indicate that $\Delta_E\langle 100\rangle$ is not zero and, in fact, upon reanalysis show that Δ_E is a maximum in the ⟨100⟩ direction. Experiments on the b.c.c. Li−Mg alloy (selected because it is free of the complication of an order-disorder transformation) show an anisotropy ratio $(\Delta_E\langle 100\rangle)/(\Delta_E\langle 111\rangle)=3.1$, and thus substantiate the results on beta brass. These observations can be explained if it is assumed that next-nearest neighbor interactions, neglected in previous treatments, play a dominant role in this phenomenon.

* This work was carried out at Yale University where it was supported by the Office of Ordnance Research.
[1] D. P. Seraphim and A. S. Nowick, Bull. Am. Phys. Soc. Ser. II, 2, 123 (1957).
[2] C. Zener, Phys. Rev. 71, 34 (1947).
[3] A. D. Le Claire and W. M. Lomer, Acta Met. 2, 731 (1954).
[4] R. A. Artman, J. Appl. Phys. 23, 475 (1952).

M6. Internal Friction of Cold-Worked Copper Single Crystals. L. J. BRUNER,* *University of Chicago.*—An apparatus has been constructed for the measurement of internal friction in cold-worked copper single crystals at low temperature and in the kilocycle frequency range. Temperatures covered range from 4.5°K to room temperature. Excitation frequencies between 10 kc and 70 kc are obtained by driving the specimen bar electrostatically in successive modes of longitudinal vibration. Of particular interest are internal friction peaks observed originally by Bordoni[1] and more recently by Niblett and Wilks[2] and generally attributed to a dislocation relaxation mechanism. A detailed study of these peaks under varying conditions of specimen pretreatment is in progress.

* Crane Company predoctoral fellow.
[1] P. G. Bordoni, J. Acoust. Soc. Am. 26, 495 (1954).
[2] D. H. Niblett and J. Wilks, Phil. Mag. 2, 1247 (1957).

M7. Internal Friction in Copper Single Crystals at Low Temperatures.* V. K. PARE, T. R. CUYKENDALL, AND H. S. SACK, *Cornell University.*—The internal friction maximum first observed by Bordoni at about 80°K is of interest because it may provide information on lattice barriers to dislocation motion. Results of measurements on cold-worked copper single crystals vibrated at 4 kc are described, and compared with the 40 kc data of Caswell[1] on some of the same samples. The effects of frequency, mode of deformation, impurities, and aging on the position, height, and shape of the peak are discussed. The theory of Seeger, Donth, and Pfaff[2,3] predicts the correct general behavior but gives a peak which is much too narrow and shifts with changes in strain amplitude. Taking into account the internal stresses in cold-worked metal eliminates the latter effect and broadens the peak in a way which depends on the relaxation model used.

* This work was supported in part by the Office of Scientific Research of the U. S. Air Force.
[1] H. Caswell, Cornell thesis, 1957, and OSR Report TR-57-69.
[2] Seeger, Donth, and Pfaff, Discussions Faraday Soc. 19 (1957).
[3] H. Donth, Z. Physik 149, 111 (1957).

M8. Pressure Derivatives of the Elastic Constants of Copper, Silver, and Gold, to 10 000 Bars. W. B. DANIELS AND CHARLES S. SMITH, *Case Institute of Technology.*—The pressure derivatives of the elastic constants of the homologous series of metals copper, silver, and gold, have been measured over the pressure range from 0 to 10 000 bars, using a modified ultrasonic pulse echo method. Means have been devised to make measurement of the *change* of elastic constants with pressure as directly as possible. The values found for the pressure derivatives of the elastic constants are:

Metal	dC/dP	dC'/dP	dB_s/dP
Cu	2.35	0.580	5.59
Ag	2.31	0.639	6.18
Au	1.79	0.438	6.43

The notation, $C=C_{44}$, $C'=(C_{11}-C_{12})/2$, and $B_s=(C_{11}+2C_{12})_s/3$ has been used. The data for each metal of the three elastic constants and their pressure derivatives have been interpreted in terms of conventional theory. The theoretical contributions of long-range interactions have been subtracted off and the remainder attributed to short-range nearest neighbor interaction. The analysis indicates that these must be noncentral, many-body interactions in order to account for the shear constants and especially their pressure deriva-

tives. The many-body character of the interactions is of increasing importance in the sequence, copper, silver, and gold.

M9. Single Crystal Elastic Constants of Lithium. H. C. NASH, *John Carroll University*, AND CHARLES S. SMITH, *Case Institute of Technology*.—The adiabatic elastic constants of single crystals of lithium have been measured by the ultrasonic pulse-echo technique. The results in units of 10^{11} dyne cm^{-2} follow:

Temperature °K	C_{44}	$(C_{11}-C_{12})/2$	B_s
78	1.08	0.116	1.33
155	1.00	0.111	1.25
195	0.96	0.109	1.20

This work was undertaken for comparison with Fuchs[1] theoretical calculation of the Coulomb contribution to the shear stiffnesses of the alkali metals. In lithium, this is the only significant contribution. Extrapolation of the experimental values to absolute zero gives values for both C_{44} and $(C_{11}-C_{12})/2$ which are lower than the corresponding theoretical values. The experimental anisotropy $A=C_{44}/[(C_{11}-C_{12})/2]$ is higher than the value predicted by the theory.

[1] K. Fuchs, Proc. Roy. Soc. (London) **A153**, 622 (1936); **A157**, 444 (1936).

M10. Elastic Constants of Fe-31%Ni near the Curie Point. J. R. NEIGHBOURS, G. A. ALERS, AND H. SATO, *Ford Motor Company*.—The three elastic constants C, C', and $\frac{1}{3}(C_{11}+C_{12}+2C_{44})$ of a [110]-oriented single crystal of Fe-31%Ni have been measured from room temperature to well above the Curie temperature using the ultrasonic pulse technique. The temperature variation of the three constants is different but all show a gradually changing slope as the temperature is increased. For C' and $\frac{1}{3}(C_{11}+C_{12}+2C_{44})$ the slope changes sign, being positive at room temperature. The temperatures at which the greatest changes in slope occur are different for the three constants. At high fields, where the ΔE effect resulting from domain rotation is very small, the moduli decrease with increasing magnetic field by an amount depending on the mode and temperature. These effects may be interpreted in terms of the temperature and field dependence of the magnetization.

FRIDAY AFTERNOON AT 1:45

Mandel Hall

(J. W. BEAMS presiding)

Oliver E. Buckley Lecture

N1. Nuclear Magnetic Resonance in Solids. N. BLOEMBERGEN, *Harvard University*. (45 min.)

FRIDAY AFTERNOON AT 2:30

Mandel Hall

(CHARLES S. SMITH presiding)

DSSP Symposium

Classical Solid-State Physics

P1. X-Ray Analysis of the Structure of Cold-Worked Metals. B. E. WARREN, *Massachusetts Institute of Technology*. (30 min.)

P2. Elastic Constants and Microscopic Models. H. B. HUNTINGTON, *Rensselaer Polytechnic Institute*. (30 min.)

P3. Lattice Dynamics and Thermal Diffuse Scattering of X-Rays. E. H. JACOBSEN, *General Electric Research Laboratory*. (30 min.)

P4. Lattice Vibrations of Layer Lattices and Elastic Constants. J. A. KRUMHANSL, *National Carbon Research Laboratory*. (30 min.)

FRIDAY AFTERNOON AT 2:40

Cobb 110

(C. S. BARRETT presiding)

Metals, II

Q1. Self-Diffusion of Silver in Silver-Gold Alloys.* W. C. MALLARD AND L. SLIFKIN, *University of North Carolina*.—As the initial step in an investigation of the effect of chemical concentration gradients on diffusion coefficients in completely miscible binary alloys, the self-diffusion of tracers of silver and gold is being studied for Ag-Au alloys in the range 0 to 50

atomic % Au. Results of measurements with Ag 110 tracer in single crystals and in very coarse-grained polycrystals will be given in this paper. Values of D for diffusion in pure silver agree well with the University of Illinois work. Data obtained thus far indicate no dependence of activation energy on Au concentration, to a first approximation. The pre-exponential factor, D_0, initially decreases with increasing concentration of gold, but for 50% Au specimens D_0 is consistently 3% *greater* than the 34% Au value. This suggests that D_0 *vs* concentration may have a shallow minimum. The ratio of D_0 in alloy specimens to D_0 in pure silver is approximately 0.8 for 16 atomic % Au and 0.7 for 34 and 50% Au. Further measurements now in progress will also be described.

* Supported in part by the U. S. Atomic Energy Commission.

Q2. Anomalous Diffusion of Rare Earth Tracers in Cubic Metals.* G. P. WILLIAMS AND L. SLIFKIN, *University of North Carolina.*—To evaluate the size effect in diffusion properties, experiments on diffusion of rare earth tracers in silver and lead have been initiated. For the conventional geometry employed, Fick's law predicts a linear relation after diffusion between the logarithm of the tracer concentration and the square of the distance in from the surface, as is commonly observed. Our results deviate strongly from such behavior. The plots of log (concentration) *vs* x^2 for diffusion of C_s and P_m in Ag and in Pb at temperatures close to the solvent melting point all show a very steep initial slope, corresponding to a D of only about 10^{-11} cm²/sec, followed by a flatter region of much greater penetration but containing very little of the tracer. Such phenomena may be due to a strong enhancement of dislocation effects by the negligibly small solubility of the tracers in the solvent lattices, but they have consistently been observed in single as well as polycrystals and at tracer concentrations as low as 10^{-6} to 10^{-9} atomic fraction. Comparison of results from gamma and beta counters indicate that the same tracer is involved in both regions.

* Supported in part by the U. S. Atomic Energy Commission.

Q3. Diffusion in Inhomogeneous Media. STEPHEN PRAGER, *University of Minnesota.*—A theory is presented which gives the effective diffusion coefficient in a medium where the actual diffusion coefficient varies from point to point in a manner which is known only statistically. A rigorous expression is obtained in the form of a series, successive terms of which involve increasingly higher n-point averages of the actual diffusion coefficient and its logarithm. In addition, an approximate theory requiring only 2-point averages is developed. The results obtained may also be applied to the calculation of effective heat conductivities, electrical conductivities, and dielectric constants.

Q4. Influence of Impurities on Self-Diffusion in Metals. HOWARD REISS, *U. S. Steel Corporation.*—Recently, investigations[1,2] of the influence of impurities (Pb, Cu, Al, Ge, Sb) on self-diffusion in silver have been published. Empirically, the self-diffusion coefficient D depends on impurity content according to the rule[1] $D=D^*\exp(bx)$, (1), where D^* is the coefficient for no impurity b is constant and x is the atom fraction of impurity. For Pb, $b=10.5\exp(5000/RT)$, (2). For Cu, Al, Ge, Sb $b=\alpha/RT$, (3), where α is constant. A theory has been developed which proves (1) and shows that $b=\Sigma_{i=1}^{n}[\exp(-\varphi^i/RT)-1]$, (4), in which φ^i is the potential of average force for a vacancy at the ith lattice site about an impurity and N is the number of lattice sites per unit volume. When $-\varphi_i>RT$ for $i=1$ (the nearest sites to an impurity), while $\varphi_i=0$ for other sites, $b=z\exp(-\varphi_i/RT)$, where z is the number of nearest neighbors. This is of form (2). When $\varphi_i/RT<1$, (4) yields $b=-\varphi_i/RT$ of the form (3). It is shown that φ_i is related to the heat of solution of the impurity in the metal. For several impurities (1) is replaced by $D=D^*\exp(\Sigma b_i x_i)$.

[1] Hoffman, Turnbull, and Hart, Acta. Met. 3, 417 (1955).
[2] E. Sonder, Phys. Rev. 100, 1662 (1955).

Q5. The Effect of Simultaneous Plastic Flow on Self-Diffusion in Silver Single Crystals.* J. B. DARBY, JR., *University of Illinois,* C. T. TOMIZUKA, *University of Chicago,* AND R. W. BALLUFFI, *University of Illinois.*—Buffington and Cohen[1] found that self-diffusion in iron at 890°C was apparently increased by a factor of 15 by applying a compressive strain rate of $\dot{\epsilon}=-0.27$ hr^{-1}. This result could conceivably be caused by the generation of point imperfections during deformation or by short circuiting along dislocations and interval cracks. We have carried out somewhat similar experiments on silver single crystals orientated for duplex slip. Ag^{110} was plated on (111) and $(\bar{1}10)$ faces of the bar shaped crystals and the penetration curves were obtained by sectioning. The Gaussian curves showed no effect resulting from the deformation within the expected experimental error (measurement of the diffusivity to $\pm 20\%$) for $\dot{\epsilon}\lesssim+0.2$ hr^{-1} at 900°C and $\dot{\epsilon}\lesssim 0.03$ hr^{-1} at 800°C. The total strains were <0.35. Changes in structure were also investigated, and at 900°C recrystallization occurred during the first hour of deformation. At 800°C no recrystallization occurred during the runs. Further experiments in compression are in progress.

* Supported by the Air Force Office of Scientific Research.
[1] F. S. Buffington and M. Cohen, Trans. Am. Inst. Mining, Met. Petrol. Engrs. 194, 1085 (1952).

Q6. Tracer and Chemical Diffusion in Ag-AgCd (α-Phase) Diffusion Couples.* J. R. MANNING, *University of Illinois* (introduced by D. Lazarus).—Measurements were made in six Ag-AgCd (α-phase) diffusion couples of the diffusion of a layer of radioactive tracer atoms (either Ag^{110} or Cd^{109}) located originally at the Ag-AgCd interface. It was found that the center of gravity of the layer of tracer atoms shifted from its original position, which was marked by tungsten wires. The shapes of the tracer profiles for Ag^{110} were quite different from those for Cd^{109}, however, for both silver and cadmium tracer, the center of gravity moved toward the cadmium-rich region. The shift in center of gravity is explained as resulting from two factors, both related to the chemical concentration gradient present at the interface: (1) the chemical potential gradient in the nonideal AgCd solid solution and (2) a diffusion coefficient gradient arising because the tracer diffusion coefficients are functions of chemical concentration. The theoretically predicted shifts in center of gravity agree in both direction and approximate magnitude with the shifts found experimentally. Chemical interdiffusion and Kirkendall shift measurements were consistent, within errors, with those predicted by Darken.

* Supported in part by the U. S. Atomic Energy Commission.

Q7. Heat Capacities of Dilute Solutions of Manganese in Copper. F. E. HOARE* AND J. E. ZIMMERMAN, *Ford Motor Company.*—Measurements at helium temperatures on several Cu-Mn alloys reveal anomalously large specific heats, of the order of six times the specific heat of Cu in the same temperature interval, for Mn percentages between ½ and 4%. There are no peaks in the specific heat curves, indicating that the excess specific heats extend rather far outside the helium temperature range. These results are consistent with unpublished hydrogen-temperature measurements made by F. E. Hoare. Elastic constant measurements at room temperature on one of the specimens gave about the same result as for pure copper, indicating that the lattice specific heat cannot have been altered more than a few percent by the addition of Mn, suggesting that the excess heat capacity is of electronic origin.

* On leave from the University of Leeds.

Q8. Aging Studies in Au-Ni Alloys. JOHN SIVERTSEN AND CHARLES WERT, *University of Illinois.*—Measurements have been made of changes in some physical properties of quenched alloys of 70% Au-30% Ni when they were annealed at low temperatures. Changes in the electrical resistance, volume, and Young's modulus were observed to occur. They indicate that there is at least one metastable precipitate formed on low temperature annealing; it occurs about 10^4 times earlier than the main phase change which has been well studied previously. There is a critical temperature above which this low temperature phase is unstable; this is about 225°C. Exact description of the low temperature phase is not possible, but it does seem to be either (1) clusters of Au-rich or Ni-rich atoms or (2) regions of high geometrical order. Quenched-in vacancies are presumed to control the rate of the reaction but the precipitate is not thought to be simply clusters of vacancies.

Q9. Quench Hardening in Copper and Gold. R. MADDIN, H. KIMURA, AND D. KUHLMANN-WILSDORF, *University of Pennsylvania.*—Au and Cu show different characteristics in the hardening due to aging after quenching. The main features observed by Kauffman and Meshii[1] in Au and by the present authors in Cu are (1) the increase in the yield stress of Au is about 200%, while it is only about 50% in Cu, (2) in Au the increase is approximately proportional to the number of vacancies quenched-in for a quenching temperature range between 740°C to 930°C, while in Cu the variation of the increase with temperature is not appreciable, (3) the yield stress of Cu shows resoftening after reaching a maximum value, i.e., two hours and twenty minutes at 100°C, while resoftening in Au requires a higher annealing temperature, i.e., one hour at 700°C. We suggest that the hardening in Au quenched from above 740°C is due to the formation of sessile rings. In Cu the number of quenched-in vacancies is smaller than in Au because of its larger formation energy. The hardening and resoftening in Cu is considered to be due to the migration of vacancies toward the dislocation network.

[1] J. W. Kauffman and M. Meshii, Bull. Am. Phys. Soc. Ser. II, **2**, 145 (1957).

Q10. Oxidation of Magnesium Single Crystals at High Temperatures.* R. R. ADDISS, JR., AND H. S. SACK, *Cornell University.*—A vacuum microbalance with a sensitivity of the order of 10^{-6} g and load capacity of 0.2–0.3 g was used to study the rate of growth of oxide on the prismatic (100) plane and basal (001) plane of 99.99+% magnesium. Oxidation was carried out for periods of 5000 to 8000 minutes, at nominal temperatures of 425°C and 465°C, with an oxygen pressure of 2.5 mm Hg. Single crystal slabs of magnesium about a millimeter thick, with the large faces parallel to the desired crystallographic plane, were cut with a string saw from single crystal rods grown by the Bridgeman method; they were polished first with acid, then with emery, and finally electropolished and washed with special solutions. The geometrical areas varied from 2 to 4 cm^2. Results with the prismatic plane show a parabolic growth law in all cases, with some deviations from this law in the first 1000 min (first few hundred angstroms), and with a low activation energy (~9 kcal/mole). Results with the basal plane are similar, but show a greater initial oxidation rate with a smaller total oxidation after the first few hundred minutes. At 465°C the oxidation of the basal plane becomes linear after the first 1500 min.

* This work was supported by the Wright Air Development Center of the Air Research and Development Command and by the Office of Naval Research.

Q11. Charge and Thermodynamic Activity of a Solute Atom in Metallic Solutions. JAMES C. M. LI, *United States Steel Corporation.*—From both macroscopic arguments and the free electron model of metals, a semiempirical equation is derived for the activity coefficient of a trace component t dissolved in an ideal solvent alloy,

$$kT[\ln\gamma_t - \sum_i x_i \ln\gamma_{ti}] = \sum_{i<j} \sum x_i x_j \left[\frac{z_t \Delta_{ij}(z_i - z_j)}{\sum_i x_i z_i} + \alpha_{ijt} \right],$$

where γ_t and γ_{ti} are the activity coefficients of the trace component t in the solution and in the pure i-th component, respectively, x's are the atomic fraction, z's are the charges, Δ_{ij} is a property between the ith and jth component, and α_{ijt} is some interaction between the trace component t and the ith and the jth components in the solvent, which is not a function of composition. Both Δ_{ij} and α_{ijt} have energy units and may be functions of temperature and pressure. For the same binary solvent alloy, a plot of the left-hand side of the equation divided by x_1x_2 against $1/\Sigma_i x_i z_i$ will give a straight line with a slope proportional to z_t. This is found to be consistent with many sets of experimental data.

FRIDAY AFTERNOON AT 2:40

Social Sciences 122

(J. L. BIRMAN presiding)

Ionic Crystals

QA1. Theory of the Exciton Contribution to the Complex Dielectric Constant of Crystals. J. J. HOPFIELD, *Cornell University.*—By using a formalism in which excitons are represented by boson operators (in close analogy to spin waves), the exciton-photon interaction problem is solved without the use of perturbation theory. It is shown that the description of absorption in terms of the annihilation of a quantum or radiation with a resulting electronic transition to an exciton state is not correct. The "optical lifetime" of an exciton state for single photon decay is also not a valid concept. The correct description of the exciton-photon interaction is in terms of states which are mixtures of photons and excitons. The dielectric constant is computed from the relation between energy and wave number for these mixed states. Optical absorption occurs only when phonon interactions are introduced. Phonon-induced transitions between these mixed states can be represented by complex energies for states of real wave number. The resulting relation can be inverted to yield complex wave number as a function of real frequency. This method of computing the absorption co-

efficient is valid even though the absorption length is smaller than a wavelength. The theory enables one to compute oscillator strengths of exciton absorption lines from the experimental optical parameters.

QA2. Oscillator Strengths for the Fundamental Absorption Band of NaCl. J. R. NELSON* AND J. J. HOPFIELD, *Cornell University.*—The oscillator strengths for NaCl in the fundamental absorption band have been calculated. Following the technique set forth by Robinson[1] the complex index of refraction $N(\lambda)$ is found from experimental normal incidence reflectivity data.[2] The measured reflectivity is $|r(\lambda)e^{i\theta}|^2$, where $r(\lambda)$ is real. The phase angle $\theta(\lambda)$ is found from $r(\lambda)$ through the Kramers-Kronig relation, which involves an integration over all wavelengths. n and k ($N \equiv n - ik$) are obtained at various wavelengths from the Fresnel reflectivity equation, which relates r and θ to n and k. Using the theory[3] relating the complex index of refraction to oscillator strengths, a value of 1.2 is obtained for the total oscillator strength in the fundamental absorption band between 1640 A and 1475 A. Values of 0.6 and 0.4 are obtained for the oscillator strengths of the two prominent lines at 1560 A and 1540 A, respectively.

* Now with the Physics Group, Convair, San Diego.
[1] T. S. Robinson, Proc. Phys. Soc. (London) **B65**, 910 (1952).
[2] Hartman, Nelson, and Siegfried, Phys. Rev. **105**, 123 (1957).
[3] J. J. Hopfield (preceding abstract).

QA3. Structure in the Infrared Lattice Vibration Spectra of Polar Cubic Diatomic Crystals. E. BURSTEIN AND G. S. PICUS, *U. S. Naval Research Laboratory.*—On the basis of elementary theory, ionic cubic diatomic crystals would be expected to exhibit a single lattice vibration absorption band. Experimentally, however, the alkali halides are found to exhibit additional absorption bands on the short-wavelength side of the main band, and an additional reflection peak at shorter wavelengths than the major reflection peak. Similar structure is also observed in the absorption and reflection spectra of other crystals with NaCl and CsCl structures, such as MgO, PbS, TlCl, etc. The additional bands are attributed by Born and Blackman to anharmonic terms in the potential energy. It has also been suggested that they may arise from second order terms in the electric moment.[1] Recent infrared studies of a variety of crystals with ZnS structure indicate that, unlike NaCl and CsCl type crystals, the ZnS type crystals have much less pronounced structure in their absorption spectra and exhibit only one reflection peak.[2] This difference in behavior of the two groups of crystals is correlated with differences in their thermal coefficients of expansion. It suggests that the additional structure in the infrared lattice vibration spectra is due to mechanical anharmonicity rather than to electrical anharmonicity.

[1] M. Lax and E. Burstein, Phys. Rev. **97**, 39 (1955).
[2] Picus, Burstein, and Henvis, Bull. Am. Phys. Soc. Ser. II, **1**, 126 (1956).

QA4. Binding Energy for a Self-Trapped Hole in NaCl. J. YAMASHITA, *University of Illinois.*—The possibility that an electron can trap itself in a polar crystal was discussed by many authors, but there had been no reliable experimental evidence of the trapping till Känzig and others found "the self-trapping of a hole" in the form of a $(Cl_2)^-$ molecule in alkali-halide crystals. We shall investigate in detail the possible mechanism of the self-trapping of a hole by computing the binding energy of the self-trapped hole in NaCl. We use two alternative approximations: one is the adiabatic approximation of Landau-Pekar with the continuum model; the other is the point dipole model which was developed by Mott-Littleton and Markham-Seitz.

QA5. Thermal Conductivity of KCl and NaCl above Room Temperature.* W. H. BESSEY, H. BROWN, W. MILLER, P. OHLSEN, AND H. WEISBROD, *Missouri School of Mines and Metallurgy.*†—The thermal conductivities of single crystals (from Harshaw) of NaCl and KCl have been determined in the temperature range 100°C to 400°C by a simple steady-state guard-ring method. Temperatures were determined and controlled by chromel-alumel thermocouples. Logarithmic plots of conductivity *versus* temperature are straight lines of negative slope 1.2 to 1.3 for both materials, instead of negative slope unity as predicted by simple theory.

* Supported by a grant from the Research Corporation.
† Now at Butler University, University of Missouri, Convair, North American Aviation, and Olin-Mathieson, respectively.

QA6. X-Ray Coloration and Expansion of NaCl Single Crystals. HERBERT RABIN, *U. S. Naval Research Laboratory.*—Coloration and expansion measurements of undoped and doped NaCl crystals have been made under 43 kvp tungsten x irradiation. The undoped crystals include those from the Harshaw Chemical Co., the Optovac Co., a natural crystal from near Baden, Germany, and an NRL Kyropolus-grown crystal. From the same NaCl batch, doped crystals were also grown at NRL with KCl, $CaCl_2$, and $CdCl_2$ added in amounts up to one mole percent in the melt. F-band absorption measurements were made with a Cary spectrophotometer and expansion was measured continuously with a sensitive capacitive dilatometer designed to compensate for thermal fluctuations. The initial linear relation between relative expansion and F-center density reported by Lin[1] is obtained for all crystals measured; however, the relative expansions per F center are somewhat smaller. Of all crystals measured the natural (Baden) NaCl is found both to color and expand the least. The increase in F-band coloration under x-rays by the addition of calcium to NaCl is not accompanied by a corresponding increase in expansion. The detailed coloration and expansion growth curves will be presented.

[1] L. Lin, Phys. Rev. **102**, 968 (1956).

QA7. Optical Properties of Sodium Chloride Containing Colloids. HOWARD W. ETZEL, *U. S. Naval Research Laboratory.*—The extinction of single crystals of sodium chloride, which have been additively colored and slowly cooled, has been measured from 1000 mμ to 185 mμ. In addition to a colloid band which shows marked light scattering in the visible region of the spectrum, three bands are observed in the ultraviolet region at 288 mμ, 228 mμ, and 192 mμ. Irradiation into the 228-mμ band using a cadmium arc lamp through a monochromator decreases this band and produces F centers in the crystal. At room temperature the yield is 0.6 F centers formed per quantum absorbed. If such an F-centered crystal is heated to 250°C a colloid band forms in the visible region which does not show light scattering. It is possible that the band at 192 mμ is the well-known U band. If a colloidal bearing crystal is hydrided at 750°C a U band forms at 192 mμ. The likelihood that "precursors" are actually U centers will be discussed.

QA8. Thermal Conductivity of Lithium Fluoride at Low Temperatures.* M. MOSS, R. L. SPROULL, AND H. WEINSTOCK, *Cornell University.*—The thermal conductivities of Harshaw LiF crystals (6×6×40 mm) were measured over the temperature range 3°–100°K in the apparatus described by Williams.[1] Crystal #1 was cleaved and not subsequently annealed. Crystal #2 was annealed at 820°C for 2½ hr and cooled slowly (~12 hrs) to room temperature. The thermal conductivity K of #1 agreed closely with the measurements of Berman, Foster, and Ziman.[2] K for #2 was the same above

30°K but its maximum value (38 watts/cm deg at 12°K) was a factor of 2 greater than that of #1. K of #2 was approximately proportional to T^3 from 3°–10°K. Limitation of K below 15°K by linear imperfections in these crystals is thus indicated, but etch pit counts showed too few dislocations by a factor of about 100 to account for the T^3 scattering.

* Supported in part by the National Science Foundation.
[1] W. S. Williams, Bull. inst. intern. froid Suppl., Commission 1 et 2, Louvain, 1956, Annexe p. 119 (1956).
[2] Berman, Foster, and Ziman, Proc. Roy. Soc. (London) **A237**, 344 (1956).

QA9. Effect of Dislocations on Low Temperature Thermal Conductivity.* R. L. SPROULL, M. MOSS, AND H. WEINSTOCK, *Cornell University.*—Crystals of Harshaw LiF about 6×6×40 mm were deformed in compression along the 40-mm direction ([100]) with support along the other directions to prevent buckling. In crystal A the long dimension was reduced ~4% by compression at 180°C, and in crystal B it was reduced ~2% at 25°C. Etch pit counts based on the work of Gilman and Johnston[1] indicated dislocation densities of 4.6×10^7 lines/cm^2 in A and 1.8×10^7 lines/cm^2 in B without appreciable clustering. The thermal conductivity of A was about $0.027T^{1.8}$ watts/cm deg and of B about $0.043T^{2.0}$ watts/cm deg between 2° and 10°K. The thermal resistivity below 10°K was therefore approximately proportional to T^{-2} and to the dislocation density. The temperature dependence supports Klemens'[2] theory of the scattering of phonons by dislocations, but the observed magnitude exceeds the calculated magnitude by a factor of ~10[2].

* Supported in part by the National Science Foundation.
[1] J. J. Gilman and W. G. Johnston, J. Appl. Phys. **27**, 1018 (1956).
[2] P. G. Klemens, Proc. Phys. Soc. (London) **A68**, 1113 (1955).

QA10. Luminescence of "Pure" Alkali Iodides.* R. F. WEEKS AND K. J. TEEGARDEN, *University of Rochester.*—Further measurements on the low temperature luminescence of "pure" alkali iodides excited by light in the region of the fundamental band have been made. Previously reported work on the luminescence of KI[1] has been extended to include measurements of the lifetime of the luminescence and the temperature dependence of the quantum yield. A study has also been made of the luminescence of "pure" RbI. The results of this work will be discussed in terms of possible models for the electronic processes involved in the luminescence.

* Research supported in part by the U. S. Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command.
[1] K. J. Teegarden, Phys. Rev. **105**, 1222 (1957).

QA11. Transient Photoconductivity in AgCl at Low Temperatures.* ROGER VAN HEYNINGEN AND FREDERICK C. BROWN, *University of Illinois.*—Primary photoconductivity has been investigated down to 6.5°K in single crystals of pure AgCl using low intensity, monochromatic light pulses and a sensitive electrometer. It is found from the spectral response with applied voltages of both polarities that only electrons have a measurable range in air or vacuum grown crystals. The electron yield per absorbed photon (quantum efficiency) can be determined as a function of wavelength from the experiment. In all crystals it shows structure and is high, decreasing from ~0.7 at the absorption edge, 385 mμ, through the first absorption peak to ~0.1 at 220 mμ. Moreover, quantum efficiency is the same at 35°K as at 77°K and is comparable at 6.5°K. Trapping greatly reduces the electron range at low temperature (~10^{-4} cm^2/volt at 77°K; ~10^{-9} cm^2/volt at 6.5°K]. Characteristics of the most important traps can be deduced from prominent electrical glow peaks observed at 15°K, 35°K, and 180°K, as well as from current decay measurements and trap filling experiments at fixed temperatures. The deep, 0.55 ev, traps are present in concentrations of 10^{12} cm^{-3} (air grown crystals) to 10^{15} cm^{-3} (vacuum grown) and have a large cross section, ~10^{-13} cm^{-2}. The shallow traps are present in much higher concentration.

* Partially supported by the U. S. Air Force.

QA12. Drift and Diffusion of Photoelectrons in AgCl at Room Temperature.* FREDERICK C. BROWN, *University of Illinois.*—Although AgCl is an ionic conductor at 300°K it is possible to study transient photoconductivity by using short (0.2 μsec) light pulses synchronized with pulses of applied voltage.[1] Single crystals can be prepared in which electrons released into the conduction band by light remain free for times as long as 50μsec before being trapped in deep states. Holes appear to be very immobile in AgCl and electron-hole recombination processes relatively unimportant. At low voltages photocurrent decay times are a direct measure of electron trapping times. These times are the same whether the crystal is illuminated in the volume or by strongly absorbed light near one surface (electrons separated from holes by electric field). At higher voltages a sheet of electrons can be injected at the cathode and collected at the anode. The transit times yield values of drift mobility about equal to Hall mobility. The spread in time of arrival at the anode is in agreement with the Einstein-Nernst relation relating diffusion constant and mobility only in the limit of low intensity. At high light intensity space charge effects increase the width of the observed collection pulse and cause it to be asymmetrical.

* Partially supported by the U. S. Air Force.
[1] F. C. Brown, J. Chem. Phys. Solids (to be published).

QA12. Self-Diffusion of Thallium in Thallium Chloride. R. J. FRIAUF, *University of Kansas.*—Preliminary measurements have been made on the diffusion of radioactive Tl^{204} in single crystals of thallium chloride by the sectioning method. Between 250 and 350°C the observed diffusion coefficient for thallium is considerably smaller than the value calculated from the total ionic conductivity by using the uncorrected Einstein relation. It appears likely from these results that Schottky defects are present, with thallium vacancies considerably less mobile than chlorine vacancies, in agreement with previous qualitative results obtained from the conductivity of TlCl doped with Pb and Sr.[1] When the Bardeen-Herring correlation factor of 0.655 for the diffusion of thallium vacancies on a simple cubic lattice is applied,[2] it can be calculated that thallium ions account for approximately 1/30 of the total current. Further measurements are planned to extend the temperature range for thallium diffusion and to investigate the diffusion of chlorine.

[1] K. Hauffe and A.-L. Griessbach-Vierk, Z. Elektrochem. **57**, 248 (1953).
[2] K. Compaan and Y. Haven, Trans. Faraday Soc. **52**, 786 (1956).

QA13. Microwave Dielectric Constant of Silver Bromide. GEORGE E. SMITH* AND ANDREW W. LAWSON.—A study has been made of the dielectric constant and dielectric loss of silver bromide at 23.3 kmc between 0°C and 400°C. The method consists of placing a sample at the end of a short circuited line and measuring the complex impedance with and without the sample in place. The dielectric constant shows a rapid increase near the melting point to about twice the room temperature value. A pronounced peak in the dielectric loss has been observed at 190°C and a broader peak at 10°C. The probable origin of these peaks and the change in dielectric constant will be discussed in terms of the lattice imperfections present. Comparison will be made with cadmium doped samples.

* Predoctoral National Science Foundation Fellow.

FRIDAY AFTERNOON AT 2:40

Kent 107

(HARVEY BROOKS presiding)

Various Topics in Semiconductor Physics

R1. Gray Tin Single Crystals.* O. N. TUFTE AND A. W. EWALD, *Northwestern University.*—Single crystals of gray tin having dimensions of the order of a centimeter have been grown from mercury solution. These crystals are bounded by well developed and highly reflecting planes, usually those of {100} and {111} form. The gray tin structure as well as a high degree of crystalline perfection have been confirmed by x-ray examination. Residual resistance measurements indicate a total impurity content less than 0.001%. Both n- and p-type crystals have been obtained, the type being determined by growth conditions and impurities originally present in the mercury. The intrinsic conductivity which extends down to -100°C yields an energy gap of 0.08 ev as for transformed gray tin. Preliminary measurements of the magnetoresistance coefficient of an n-type sample show (at nitrogen temperature) an 8-fold increase over the value for high-purity transformed tin indicating a considerably higher mobility.

* Supported by the Office of Naval Research.

R2. Exciton Absorption of the Direct Transition in Germanium.* SOLOMON ZWERDLING, LAURA M. ROTH, AND BENJAMIN LAX, *Lincoln Laboratory.*—Exciton absorption of the direct transition in germanium has been observed at 77°K, 4.2°K, and 1.5°K with a high-resolution grating spectrometer. The magnetoabsorption of the first two exciton lines has been studied up to 38.9 Kg and showed nonlinear behavior at the lower fields. The binding energy of the exciton at zero field was determined to be ~0.0025 ev as compared to a theoretical value[1] of 0.0017 ev from $E_N \approx 13.60\,\mu^*/K^2N^2m_0$, where $\mu^*=0.031\,m_0$ is a reduced mass, $K=16$ is the dielectric constant, and N is the exciton quantum number. The experimental binding energy at 38.9 kg was 0.0043 ev as compared to 0.0045 ev calculated from the results of Yafet, Keyes, and Adams.[2] The expected fine structure of the first exciton line, due to degeneracy of the valence band, was not resolved. However, the broadening of this line at the highest field was approximately threefold.

* The research reported in this document was supported jointly by the Army, Navy and Air Force under contract with the Massachusetts Institute of Technology.
[1] G. Dresselhaus, J. Phys. Chem. Solids 1, 14 (1956); R. J. Elliott (to be published).
[2] Yafet, Keyes, and Adams, J. Phys. Chem. Solids 1, 137 (1956).

R3. Interpretation of the Magneto-Absorption Spectrum in Ge and InSb.* LAURA M. ROTH, BENJAMIN LAX, AND SOLOMON ZWERDLING, *Lincoln Laboratory.*—A detailed analysis of the fine structure of the oscillatory magneto-absorption spectrum of the direct transition in germanium[1] was made using the Luttinger-Kohn model of the valence band levels with selection rules $\Delta n=0, -2$ and additional selection rules for m_j (valence band), and m_s, (conduction band), i.e., $\Delta m=0$ for $\mathbf{E}\|\mathbf{B}$ and $\Delta m=\pm 1$ for $\mathbf{E}\perp\mathbf{B}$. The spin splitting of the electron levels gives a g factor of -3. The decrease in curvature of the conduction band was quantitatively determined. The oscillatory magneto-absorption data at 300°K in InSb was also analyzed taking into account the spin-orbit effect on the conduction levels. The splitting of the first two transmission minima was in good agreement with the theoretical g factor of -50. A theoretical analysis of the indirect transition magneto-absorption spectrum in Ge indicates a nonoscillatory character. A similar analysis of the magneto-absorption spectrum for the vertical transition between the top of the valence band and the lower splitoff band predicts the existence of both oscillatory and nonoscillatory components. Calculations indicate that the low temperature, high resolution apparatus[1] should detect these two sets of spectra.

* The research reported in this document was supported jointly by the U. S. Army, Navy, and Air Force under contract with M.I.T.
[1] Zwerdling, Lax, and Roth, Bull. Am. Phys. Soc. Ser. II, 3, 16 (1958).

R4. Properties of Ag-Doped Germanium. W. W. TYLER, *General Electric Research Laboratory.*—Copper, silver, and gold constitute the IB column of the periodic table with configurations $3d^{10}4s^1$, $4d^{10}5s^1$, and $5d^{10}6s^1$, respectively. The observation that Cu and Au act as triple acceptor impurities[1] in Ge suggests similar behavior for Ag. Acceptor levels attributable to Ag have been observed at 0.14 ev from the valence band and at 0.25 ev and 0.10 ev from the conduction band. These constitute a set of acceptor levels intermediate between those observed for Cu and Au. Whereas both Cu and Au in Ge have distribution coefficients of about 10^{-5} and maximum solubilities of $\sim 2\times 10^{16}$ cm^{-3}, the corresponding quantities for Ag are $k_0=3\times 10^{-7}$ and $c_m=5\times 10^{14}$ cm^{-3}.[2] Information derived from chemical and optical properties and from spectroscopy indicate that the d shell in Ag is appreciably deeper than in Cu and Au. This suggests that the relative solubility of these elements in Ge may be related to the energy necessary to promote d electrons rather than to atomic radii.

[1] H. H. Woodbury and W. W. Tyler, Phys. Rev. 105, 84 (1957).
[2] Solubility values deduced from electrical measurements have been substantiated by R. O. Carlson using radio-tracer techniques.

R5. Absorption Spectra of III, V Impurities in Germanium.* P. FISHER AND H. Y. FAN, *Purdue University.*—Ionization and excitation absorption of some III and V impurities have been observed in germanium. P, As, Sb, and Bi show strong bands at 111, 99.8, 151.5, and 113 μ, respectively. Also, As, Bi, and P show bands at 131, 152.6, and 151 μ, respectively; in the latter two cases, the band seems to have two unresolved bands. The strongest band can be identified with the $(1s-2p,\pm 1)$ transition and the second band with $(1s-2p,0)$, in the level scheme of Kohn.[1] In each case the energy difference between the two bands agrees well with the calculated value. In addition, As shows a band at 106.8 μ $(1s-3p,0)$; however, a band at 151 μ and probably another at 122 μ have no place in the calculated energy levels. Also, a 135.5 μ band in Bi and 186.8 and 193.3 μ bands in Sb cannot be identified. For the acceptor impurity, Ga, bands have been observed at 135, 148, 171, and 185 μ, the first two being the strongest. The first three may be associated with the $2p^{(3)}$, $2p^{(2)}$, and $2p^{(1)}$ levels.

* Work supported by the Office of Naval Research.
[1] W. Kohn, *Solid State Physics* (Academic Press, Inc., New York, 1957), Vol. 5, p. 257.

R6. Interaction Between Lithium and Oxygen in Silicon. E. M. PELL, *General Electric Research Laboratory.*—When lithium is diffused at 800°C into silicon containing up to 1.3×10^{18} oxygen atoms/cc, it removes the 9-μ infrared

absorption peak, and the peak does not return when the lithium is precipitated at temperatures between 20°C and 200°C. This indicates that the Li reacts chemically with the oxygen, breaking the Si-O bonds responsible for the 9-μ absorption. During precipitation, the free electron concentration drops exponentially with time until it saturates at a level equal to the oxygen concentration, suggesting the formation of a donor complex of the form Li_nO^+. The precipitation kinetics are in quantitative agreement with the size and concentration of precipitate particles revealed by the electron microscope. The concentration of precipitate particles, as determined from the precipitation kinetics, appears to be proportional to the oxygen concentration. If the sample is held at the precipitation temperature, the free carrier concentration—presumably from Li_nO^+—decreases further with a much longer time constant eventually saturating at a second plateau which is independent of temperature and related to the oxygen content. Precipitation rates and complex concentrations indicate that vacuum melted floating zone Si contains about 10^{18} oxygen atoms per cc.

R7. Effect of Irradiation on the Infrared Absorption in Silicon.* H. Y. Fan and A. K. Ramdas, *Purdue University.*—Infrared absorption bands produced by irradiation in silicon have been studied.[1] Annealing up to 230°C showed that the 1.8-μ band anneals out with an activation energy of ~0.2 ev. Spitzer and Fan[2] observed a band at 3.9 μ in an impure p-type sample bombarded with 8.5×10^{18} neutrons/cm^2, which became more pronounced after annealing. This became unobservable with further annealing and a very strong band developed around 6 μ, which increased with more annealings at 170°C and 200°C. The resistivity of the sample decreased with annealing and the Fermi level moved closer to the valence band. Study of samples of different initial carrier concentrations and subjected to various bombardment and annealing schedules showed that the 3.9- and the 6-μ bands can be observed only when the Fermi level is sufficiently close to the valence band. An irradiated n-type sample did not show these bands; instead a band at 3.3 μ was observed. Experiments are being made to determine whether the defects responsible for these bands were introduced directly by bombardment or developed by the annealing.

* Supported by a Signal Corps contract.
[1] Becker, Fan, and Lark-Horovitz, Phys. Rev. **85**, 730 (1952); H. Y. Fan, Repts. Progr. Phys. **XIX**, 107 (1956).
[2] Spitzer and Fan, Phys. Rev. (to be published).

R8. Infrared Absorption Spectra of n-Type Impurities in Silicon. G. S. Picus, B. W. Henvis, and E. Burstein, *U. S. Naval Research Laboratory.*—Far infrared transmission spectra for silicon doped with Sb and As to a concentration of approximately 10^{18} atoms/cc have been measured and the data have been extended to wavelengths up to 48 μ. The materials used were obtained from Texas Instruments, Inc., through the courtesy of Dr. W. Adcock. A strong absorption peak is found at 39.5 μ in Sb-doped Si in agreement with what would be expected on the basis of the Kohn-Luttinger[1] theory and the previous data.[2] For As-doped Si a line not previously attributed to As is now confirmed at 31.6 μ and another strong line is observed at 36.2 μ. Another line at 36.5 μ, again beyond those previously noted, is also observed in P-doped Si. This measurement was made on one of the samples used in the previously reported investigations.[2] With the inclusion of the new lines, agreement is no longer obtained between the experimentally observed spectra and that derived from the term scheme proposed by Kohn and Luttinger so that it is no longer possible to determine the optical ionization energies by use of that term scheme.

[1] W. Kohn, and J. M. Luttinger, Phys. Rev. **98**, 915 (1955); W. Kohn Phys. Rev. **98**, 1856 (1955).
[2] Picus, Burstein, and Henvis, J. Phys. Chem. Solids **1**, 75 (1956).

R9. Determination of a Discrete Trapping Level in CdS by Space-Charge Current Measurement. Roland W. Smith, *RCA Laboratories.*—A low-density, $\sim10^{14}$ per cc, discrete level is detected at 0.66 ev from the conduction band in CdS from space-charge current data.[1] The current-voltage curve, of a Cu-doped photosensitive CdS:Cl crystal, has two branches. In the lower branch $I\alpha\theta V^2$, while in the upper branch the current rises extremely rapidly. The V^2 part corresponds to the Fermi level moving upwards from ~0.96 ev (crystal in dark) in an essentially trap-free (e.g., $N_t\lesssim10^{10}$ per cc at $E_F\sim0.96$ ev) region in the forbidden band. θ is the ratio of free electrons to those in "shallow" traps. The "vertical" part of the characteristic[2] follows the complete filling of the trapping level at 0.66 ev by space-charge electrons.

[1] R. W. Smith and A. Rose, Phys. Rev. **97**, 1531 (1955).
[2] M. A. Lampert, Phys. Rev. **103**, 1648 (1956).

R10. "New" Type of Semiconductor Amplifier: The Electrolyte Field Effect. J. F. Dewald, *Bell Telephone Laboratories.*—A "new" type of field-effect transistor has been devised and operated in the audio range of frequency. It uses ZnO as the semiconductor and applies the modulating fields by means of a highly conducting electrolyte; the very small effective plate-separation (a few A at most) achieved with the electrolyte allows operation under the large enrichment condition which swamps out surface-state trapping effects and yields a nicely linear characteristic when operated in a cathode follower circuit. Average surface mobilities under large enrichment conditions are approximately 50% of the bulk mobility. The basic theory of the device is described and operating characteristics of a few preliminary units are presented.

R11. Efficiency of a Thermoelectric Engine. S. Machlup, *Western Reserve University.*—The appearance of semiconducting compounds with high thermoelectric powers (positive or negative, for n- or p-type doping) has revived interest in the thermocouple as a possible generator of low-voltage dc power.[1] The problem of finding the most efficient operating conditions for such an "engine" involves balancing loss due to Joule heating (important for large currents) against loss due to heat conduction (important for small currents). In the approximation of a small temperature difference ($\Delta T\ll T$) the maximum efficiency is achieved at a current $I=\frac{1}{2}\Delta T(S_A-S_B)/(R_A+R_B)$, where A and B refer to the two conductors, S is thermoelectric power, and R, resistance. The corresponding efficiency is

$$e_{\max}=\frac{1}{4}\frac{(S_A-S_B)^2\Delta T}{(R_A+R_B)(W_A^{-1}+W_B^{-1})}$$

where W is the thermal resistance. This can be further maximized with respect to variation of the thickness and length of the conductors. Assuming the law of Wiedemann and Franz, $R/W=LT$, the maximum efficiency becomes $e_{\max}=\frac{1}{16}L^{-1}(S_A-S_B)^2\Delta T/T$. However, this can not be achieved in semiconductors, where the contribution of the lattice thermal conductivity results in a larger R/W ratio.

[1] T. S. Shilliday, J. Appl. Phys. **28**, 1035 (1957); also references cited therein to the work of the Leningrad group under A. F. Ioffe.

FRIDAY AFTERNOON AT 2:40

Eckhart 133

(E. R. FITZGERALD presiding)

High-Polymer Physics

SA1. Time and Temperature Dependence of the Yield Stress in Polyethylene Terephthalate. D. W. VANAS AND B. W. STRAUBE, *Eastman Kodak Company* (introduced by M. H. VanHorn).—The effect of time and temperature on the yield stress of oriented and crystalline polyethylene terephthalate is amenable to treatment by standard techniques of viscoelasticity. By this means, it is shown that the effect of decreasing testing rate is equivalent to that of increasing the temperature. Consequently, it is possible to predict the response of this material to strain environments outside the normal range of testing conditions. It is further noted that the temporal dependence of the yield stress is analogous to that found for the rupture stress by creep experiments on polymethyl methacrylate and polystyrene.[1]

[1] F. Bueche, J. Appl. Phys. **28**, 784 (1957).

SA2. The Orientation of Crystalline Polymers.* RICHARD S. STEIN AND DONALD LEGRAND, *University of Massachusetts.*—The state of orientation of the crystals in a crystalline polymer may be characterized by three functions. Two of these describe the orientation of two of the crystal axes with respect to the stretching or machine direction and range from $+1$ for perfect parallel orientation of the axis to $-\frac{1}{2}$ for perfect perpendicular orientation. These are zero for random orientation. The variation of these two functions during mechanical or thermal processing may be represented by the movement of a point on a two-dimensional plot. The other two functions describe the cylindrical orientation of the two crystal axes with respect to the plane of the film. They range from $+1$ for orientation of an axis in the plane of the film to -1 for orientation perpendicular to this plane. They are zero for random (uniaxial orientation). The determination of these orientation functions from Geiger-counter x-ray spectrometer measurements is described and illustrated, both for cases of uniaxial and biaxial orientation. These functions uniquely determine the crystalline contributions to infrared dichroism and birefringence. The calculation of these quantities is illustrated, and the results are compared with experimental measurements.

* Supported in part by a contract with the Office of Naval Research and by grants with the Monsanto Chemical Company and the Plax Corporation.

SA3. Theoretical Values of the Dynamic Stretch Moduli of Fiber-Forming Polymers. W. JAMES LYONS, *Textile Research Institute.*—Employing concepts first applied to textile fibers by Meyer and Lotmar[1] in calculating the dynamic Young's modulus of cellulose, the modulus of polyhexamethylene adipamide (66 nylon) has been derived. The treatment employs interatomic force constants calculated from Raman and infrared spectral data, applied to a molecular geometry deduced from the crystal structure of 66 nylon determined by Bunn and Garner.[2] The modulus of the crystal cell, which would be that of a 66-nylon fiber having perfectly oriented, efficiently packed molecules, is found to be 11.5×10^{11} dynes-cm^{-2}. This value is about one order of magnitude larger than that found experimentally.[3,4] Similarly, preliminary considerations of the theoretical modulus of polyethylene terephthalate (Dacron) will be given.

[1] K. H. Meyer and W. Lotmar, Helv. Chim. Acta **19**, 68 (1936).
[2] C. W. Bunn and E. V. Garner, Proc. Roy. Soc. (London) **A189**, 39 (1947).
[3] J. W. Ballou and S. Silverman, Textile Research **14**, 282 (1944).
[4] W. J. Lyons, Textile Research J. **19**, 123 (1949).

SA4. Formation of Negatively Birefringent Spherulites in Polyhexamethylene Adipamide (66 Nylon). F. KHOURY,* *Fabric Research Laboratories, Inc.*—Recrystallization of 66 nylon at and above the optical melting point of the polymer has been studied. When heated at constant temperature in the range (~250–265°C) the polymer originally crystallized in the form of positively birefringent spherulites, melts and subsequently recrystallizes at the same temperature in the form of negatively birefringent spherulites. The number of spherulites formed, and their birefringence, decreases as the temperature at which the polymer is heated in the range (~250–265°C) is increased. In the limit at 265–266°C "nonbirefringent" spherulites are formed in the polymer. No crystallization has been detected in polymer heated at constant temperatures above 266°C. Negative spherulites are found to grow from predetermined nuclei which persist in the melt above the optical melting point of the polymer. The decrease in the number of spherulites, and hence of effective nucleation centers, with increase in temperature is taken to indicate that nucleation is from polymer aggregates or crystallites and not from foreign particles. Additional evidence is provided to support this view. The optical melting point of the negative spherulites is 268–270°C. Spherulites formed at 260°C have a degree of crystallite perfection comparable to that of undrawn annealed nylon yarn. Etching experiments indicate that the crystallinity of the spherulites varies inversely with the temperature at which they are formed.

* This work was carried out during the author's association with British Nylon Spinners Ltd. Pontypool, Mon., England, to which thanks are due for permission to publish.

SA5. Dielectric Loss in 66 Nylon—Effect of Radiation-Induced Cross-Linking and Hydrogen-Bonding Solutes. R. H. BOYD, *E. I. du Pont de Nemours and Company.*—The dielectric loss in 66 Nylon has been studied over a range of temperatures (−40–100°C) and frequencies (50 cps–70 Mc). The effects of radiation-induced crosslinking and of hydrogen-bonding solutes (4 concentrations of water and methanol and ethanol) on the orientation of dipoles have been studied. Evidence is presented for the conclusion that the chain dipole orientation mechanism is similar to that in amorphous polar polymers, but that superposition of time and temperature does not hold. The effect of crosslinking on the loss region provides a semi-quantitative measure of the chain segment length involved in the activation process. Conclusions are drawn as to the effect of hydrogen-bonding solutes on interchain binding and the activation process.

SA6. Molecular Motion in Polypropylene, Isotactic and Atactic. W. P. SLICHTER AND ELAINE R. MANDEL, *Bell Telephone Laboratories.*—Molecular order and motion in isotactic and atactic polypropylene molecules have been studied by proton magnetic resonance methods over the temperature range 77–350°K, and by x-ray diffraction at room temperature. From the temperature dependence of the second moment of the proton absorption, it is seen that some motion persists at the lowest temperatures studied, and becomes more pronounced, on the scale of the rather low frequencies in question, in the temperature interval 80–110°K. This behavior is virtually the same for both isotactic and atactic polymers, and is ascribed to motion of methyl groups about the threefold axis. The resonance curve undergoes

further narrowing near room temperature for the atactic polymer, presumably owing to torsional motions of chain segments. The narrowing occurs 20–30° higher with the isotactic compound, evidently owing to motion of the amorphous chain segments. Motions of the chains are more constrained than in polyethylene. This contrast is shown both by the proton resonance studies and also by x-ray studies of quenched isotactic polypropylene, which reveal only a minor increase in crystallinity at room temperature after 30 hr at room temperature, in comparison with the rapid crystallization in polyethylene.[1]

[1] Hopkins, Baker, and Howard, J. Appl. Phys. 21, 208 (1950).

SA7. Segmental Motion in Polypropylene and Other Poly-α-Olefins. J. A. Sauer, R. A. Wall, N. Fuschillo, and A. E. Woodward, *The Pennsylvania State University.*—Molecular motion in polypropylene has been studied both by measurements of dynamic mechanical properties and by observations of nuclear magnetic resonance line shapes. The mechanical measurements were made in the audio-frequency region and over the temperature range from 80°K to the melting point. Both completely amorphous and highly crystalline samples of polypropylene were investigated. In the amorphous sample, two transitions were observed, a broad but weak secondary one near 235°K and a relatively sharp primary one occurring above 270°K. For the highly crystalline polypropylene, two transitions occurring at 250°K and 300°K, respectively, are associated with increased mobility in the amorphous regions and a third higher temperature transition is associated with crystalline melting. These transitions have also been investigated by observing the changes occurring in NMR line shapes as the temperature is varied. The nuclear magnetic resonance measurements have also been used to study molecular and segmental mobility in the other branched poly-α-olefins such as polypentene and polybutene.

SA8. Internal Order in Native Cellulose by X-Ray Diffraction Methods.* J. H. Wakelin, H. S. Virgin, and Eugene Crystal, *Textile Research Institute.*—Two methods have been developed for evaluating the crystalline content of cotton cellulose. By the first, or correlation method, the average crystalline content of six varieties of cotton was found to be 68%; by the second, or included area method, applied to the same data, the average crystalline content was found to be 78%. For native cellulose treated with ethylamine the average crystalline contents, determined by the same methods, were 29% and 53%, respectively. The correlation method with reference to Cellulose I measures the quantity of crystalline Cellulose I in cotton, while the included area method measures the quantity of crystalline cellulose in cotton regardless of crystal type.

* Work undertaken for the Agricultural Research Service, the U. S. Department of Agriculture (Southern Regional Utilization Branch).

SA9. Volume-Temperature Relations and Proton Resonance in Unirradiated and Irradiated Polyethylene. N. Fuschillo, D. W. Krautkopf, and J. A. Sauer, *The Pennsylvania State University.*—Volume-temperature relations for various polyethylenes, both irradiated and nonirradiated, have been determined in a multiple specimen displacement dilatometer. The instrument permits measurements to be made over a wide temperature range and on samples exposed to identical temperature-time conditions. The samples studied include 3 "high-pressure" polyethylenes having various branching ratios, one "low-pressure" polyethylene (Marlex-50), 4 pile irradiated samples having thermal neutron doses of 0.3, 0.7, 2.74, and 5.5×10^{18} *nvt*, respectively, and one 300 MR Co^{60} irradiated sample. The highly branched specimen exhibited V-T relationship similar to those described by Nielson and characterized by a lower temperature melting of the crystalline regions whereas the Marlex-50 showed a relatively sharp crystalline melting transition. For the irradiated samples the melting point at which all crystallinity disappeared decreased by less than 4° for all the samples studied. Above the melting temperature the slopes of the V-T curve showed a marked decrease with increased radiation dose, but there was little change of slope at low temperatures. NMR line shapes have also been observed for many of these same samples and the combined results of the NMR data, thermal data, and available dynamic mechanical data are used to draw observations and conclusions concerning the onset of molecular mobility and the effect of radiation on both the crystalline and amorphous regions of the polymer.

Friday Evening at 6:30

Quadrangle Club

(J. W. Beams presiding)

Banquet of the American Physical Society

After-dinner speakers: L. A. Kimpton and A. W. Lawson

Saturday Morning at 9:30

Eckhart 133

(D. L. Loughborough presiding)

High-Polymer Physics (Mostly Rubbers)

T1. Transition Temperatures of Rubbery-Type Polymers. M. L. Dannis, *The B. F. Goodrich Company.*—A differential thermal expansion apparatus has been built to measure second-order transitions in rubbery-type polymers and related materials. The height of a one cc plug of the test material is measured against a stainless steel cup by a tripod mirror

system, which reflects a spot onto a galvanometer scale. The magnification ratio depends upon both tripod size and the optical lever. Temperatures are measured by a thermocouple inserted in the polymer sample itself. Second-order transition temperatures are defined by the change of slope in differential expansion curves. Second-order transition temperatures have been measured for samples of natural rubber and balata, synthetic *cis*- and *trans*-polyisoprenes, poly (1–4) butadienes with varying *cis*- and *trans*-ratios, and several polyolefins, including polymethylene. An attempt has been made to correlate both first- and second-order transitions with structure of the polymers.

T2. Stress-Strain Equation for Rubber in Tension. W. E. CLAXTON, *Firestone Tire and Rubber Company.*—A stress-strain equation is derived for a homogeneous, isotropic material with the assumptions that, for any given homogeneous simple tensile strain, the components of the stress tensor are to the first approximation linear, homogeneous functions of the components of the strain tensor and that no volume change occurs during the deformation. Utilizing the dependence of Poisson's ratio upon the extension referred to the initial coordinates, one elastic coefficient, C_{12}, is found to be sufficient to roughly characterize the first stretch stress-strain curve. Although experimentally this elastic coefficient is found to be essentially constant for extensions greater than 250%, its value increases rapidly as zero extension is approached. This behavior agrees qualitatively with data by Blanchard and Parkinson as to the distribution of secondary bond strengths.[1] Various aspects of stress-strain and cure behavior are examined with the derived equation as a basis.

[1] A. F. Blanchard and D. Parkinson, Rubber Chem. and Technol. **25**, 808 (1952).

T3. Mechanical Behavior of a Rubber at Temperatures Through the Glass Transition Temperature. J. R. STEVENS AND D. G. IVEY, *University of Toronto.*—Stress-temperature (constant strain) and length-temperature (constant stress) measurements have been made on Paracril-5 (a butadiene-acrylo-nitrile copolymer) in the temperature range −80°C to 25°C, which includes the glass-like, transition, and rubber-like states for this material ($T_g \sim -30$°C). Time effects were observed in the transition region, but for temperature gradients used here (down to about 1°C in 4 hours) the behavior at low temperatures was unique, indicating the existence of a real transition. This behavior was independent of the strain imposed at room temperature. The shift in transition temperature (in the length-temperature work) with extension was found to give quantitative support to the theory that the transition occurs at a certain minimum volume. In the rubber-like region, behavior is quite well represented by the usual equation of state, but evaluation of parameters from the data gives more consistent results if a modified form of the equation is used.

T4. Stress-Strain Relation of Pure-Gum Rubber Vulcanizates in Compression and Tension. LAWRENCE A. WOOD, *National Bureau of Standards.*—The stress-strain relation in tension for a pure-gum rubber vulcanizate after a fixed period of creep, according to Martin, Roth, and Stiehler, is

$$F = M(L^{-1} - L^{-2}) \exp A(L - L^{-1}),$$

where F is the stress, L the relative length, and M Young's modulus; A is normally about 0.38. It is now shown from published data that the equation is also valid in compression for L as small as 0.5. The equation predicted by the statistical theory represents observed data very well in the compression region from $L = 0.5$ to 1.0. The Mooney equation is approximately valid from $L = 1.5$ to 3.5. Neither of these is satisfactory in the important intermediate region. The foregoing empirical equation represents observed data over all three regions, reducing to approximate equivalence to the two other equations in the regions where they are valid. Young's modulus M can be obtained from the intercept of a plot of $\log F/(L^{-1} - L^{-2})$ against $(L - L^{-1})$ or a plot of $F/(L^{-1} - L^{-2})$ against $(L - 1)$.

T5. Isothermal Volume Dilation Accompanying the Unilateral Extension of Rubber. F. G. HEWITT* AND R. L. ANTHONY, *University of Notre Dame.*—Using a torsion balance immersed in water and natural rubber ring specimens cured with di-tertiary-butyl peroxide, measurements were made of the isothermal volume dilation of rubber for mean extensions $\epsilon = 14$, 33, and 51%, thus extending the results of Gee, Stern, and Treloar[1] to lower strains. Chain molecular weights $M_c = 3000$, 4400, 5100, and 5500 were employed, M_c values being determined by swelling in benzene. Observed fractional volume increases ranged from 3.2×10^{-5} for $\epsilon = 14\%$ and $M_c = 5500$ to 14×10^{-5} for $\epsilon = 51\%$ and $M_c = 3000$. Using Gee's expression for the volume dilation, but obtaining the slope of the stress-strain curve from the statistical theory, curves were fitted to the data, thus evaluating the parameter K (proportional to Young's modulus). The resulting curves agree well with those of Gee, Stern, and Treloar. Additional determinations of K were made from rough stress-strain curves and from the swelling data, the internal agreement between the three determinations being fair.

* Now at College of St. Thomas.
[1] Gee, Stern, and Treloar, Trans. Faraday Soc. **46**, 1101 (1950).

T6. Influence of Strain Rate on the Yield Point and its Implications in the Cold Drawing of High Polymers. HENRY M. MORGAN, *M.I.T.*—The variation in tensile properties of undrawn high polymers with strain rate has been investigated. In particular, the yield point and the drop in force following yield have been studied. The results of these studies lead to a better understanding of the cold-drawing process and in part explain the rate dependence of the natural draw ratio.[1] Actual drawing tensions have been measured with a torsion tensiometer substituted for the cold-drawing pin. Various draw ratios and draw velocities have been studied.

[1] I. Marshall and A. B. Thompson, Proc. Roy. Soc. (London) **A221** 541–557 (1954).

T7. Ultrasonic Attenuation in $CF_2Br - CF_2Br$. B. J. WEIGMAN AND A. A. PETRAUSKAS, *University of Notre Dame.*—Ultrasonic measurements of absorption and sound velocity were carried out in $CF_2Br - CF_2Br$.[1] Measurements were made from 1 to 35 Mc/sec in the temperature range 165°K to 315°K. The activation energy was found to be 6.7 kcal/mole. The molecular structure of $CF_2Br - CF_2Br$ has the same symmetry as 2,3-dimethylbutane[2] and 1,2-dibromoethane[3] previously measured in this laboratory. The activation energy of 2,3-dimethylbutane was found to be 3.3 kcal/mole while that of 1,2-dibromoethane, which has a dipole moment in the *gauche*-state but not the *trans*-state, was found to be 16 kcal/mole. The activation energy of the $CF_2Br - CF_2Br$ can be attributed to hindered rotation about the C−C bond with a much weaker interaction with its neighbors than 1,2-dibromoethane.

[1] $CF_2Br - CF_2Br$ supplied by Minnesota Mining and Manufacturing Company.
[2] J. M. Young and A. A. Petrauskas, J. Chem. Phys. **25**, 943 (1956).
[3] Chen, Anthony, and Petrauskas, Bull. Am. Phys. Soc. Ser. II, **2**, 264 (1957).

T8. Tensile Strength of Fibers and Fiber Bundles. BERNARD D. COLEMAN, *Mellon Institute.*—The statistics of the tensile strength of classical fibers (i.e., fibers whose strength is independent of the rate of loading) is discussed. Reasons are presented for expecting that the tensile strength of long classical fibers from a common source should obey the Weibull

distribution. Daniels' statistical theory[1] of the strength of bundles of classical fibers is then applied to infinite bundles whose constituent fibers obey this distribution. It is found that the ratio of the tensile strength (in dynes cm^{-2}) of a bundle to the mean tensile strength of the constituent filaments decreases monotonically with increasing dispersion in the strength of the constituent filaments. In general, the tensile strength of a large bundle has the same order of magnitude, but is *less* than the mean strength of the component filaments. Previous calculations[2] have yielded this conclusion for fibers with a particular time dependence to their tensile strength; here it is shown that the conclusion also applies to classical fibers. Thus, although it is common practice, it is wrong to say that the strength of a large parallel array is equal to the mean strength of its members.

[1] H. E. Daniels, Proc. Roy. Soc. (London) **A183**, 405 (1945).
[2] B. D. Coleman and D. W. Marquardt, J. Appl. Phys. **28**, 1065 (1957).

T9. Dynamic Viscosity of Dilute Solutions of "Monodisperse" Polystyrene. B. H. ZIMM, *General Electric Research Laboratory.*—Using the vibrating viscometer recently described,[1] the shear resistance, i.e., the real part of the square root of the complex viscosity, has been measured on dilute solutions of two samples of what is believed to be practically monodisperse polystyrene. These samples, of molecular weight 1 100 000 and 1 700 000, were prepared by the method of Bianchi *et al.*[2] Both good and bad solvents were used, and measurements were extended to concentrations as low as 0.0025 g/ml. The values of the mechanical resistance of these polymers change more rapidly with frequency than those of ordinary polystyrenes; however, the distribution of relaxation times still seems to be broader than theoretically expected, as well as somewhat displaced toward lower frequencies.

[1] B. H. Zimm, J. Polymer Sci. **26**, 101 (1957).
[2] Bianchi, Price, and Zimm, J. Polymer Sci. **25**, 27 (1957).

SATURDAY MORNING AT 9:30

Social Sciences 122

(LOTHAR MEYER presiding)

Cryogenics

TA1. Specific Heat of He^3 below 1°K. D. F. BREWER, A. K. SREEDHAR, H. C. KRAMERS, AND J. G. DAUNT, *Ohio State University.*—The specific heat of pure liquid He^3 under a pressure of about 15 cm Hg has been measured between 0.1°K and 0.7°K using an adiabatic calorimeter similar to that used previously[1] but of volume 0.5 cc. Temperatures were determined by susceptibility measurements of a cerium magnesium nitrate specimen thermally attached to the calorimeter. Previously,[2] the lowest temperature to which such measurements have been carried down was 0.23°K and our results confirm these observations. Below 0.23°K the specific heat diminishes smoothly and appears to extrapolate linearly to 0°K with a slope of 3.75 cal/mole-deg^2, in agreement with the theoretical computations of Brueckner and Gammel.[3] The entropy at 1.5°K calculated from the measured specific heat and from the linear extrapolation to 0°K is in agreement with that deduced from vapor pressure data.[4] Measurements have also been made of the liquid under pressure and of the solid phase, the latter showing an anomaly at 0.12°K.

[1] G. de Vries and J. G. Daunt, Phys. Rev. **92**, 1572 (1953); **93**, 631 (1954).
[2] Abraham, Osborne, and Weinstock, Phys. Rev. **98**, 551 (1955).
[3] K. A. Brueckner and J. L. Gammel, Symposium on He^3, Ohio State University, August, 1957.
[4] Abraham, Osborne, and Weinstock, Phys. Rev. **80**, 366 (1950); T. R. Roberts and S. G. Sydoriak, *ibid.* **98**, 1672 (1955).

TA2. Self-Diffusion and Spin Relaxation in He^3 and in He^3-He^4 Mixtures. R. L. GARWIN AND H. A. REICH, *IBM Watson Laboratory.*—Spin-echo measurements of diffusion and relaxation in He^3 liquid show a diffusion coefficient which falls only slightly between 3° and 1.8°K and extrapolates from 1.1°K to 0°K at a finite D (about 2×10^{-4} cm^2/sec). D varies with molar volume V in the liquid as V^2 over a factor 6 in D, but simultaneous measurements of D and relaxation time T_2 in the coexisting liquid and solid show that the solid has T_2 and D three orders of magnitude less than the liquid at the same P, T, and similar V. The relaxation in the liquid and solid is a bulk phenomenon as exhibited by the exponential recovery curve rather than the distinctive characteristics of a diffusion-limited surface relaxation. D is expected to rise for pure He^3 below the degeneracy temperature, and this question is being investigated with a He^3 refrigeration system and a continuous demagnetization refrigerator. 2% He^3 in He^4 shows the expected rise in D with decreasing T below T_λ as the excitations are frozen out of the He^4, leaving only the He^4 ground state, analogous to the vacuum of quantum electrodynamics. T_1 for the He^3 does not increase as the square of the dilution, the relaxation remaining a bulk phenomenon, giving perhaps an indication of a clustering of the He^3 atoms in the solution.

TA3. New Method for the Measurement of Penetration Depth; the Maximum Electron Drift Velocity in the Superconducting State. E. ERLBACH, R. L. GARWIN, AND M. SARACHIK, *IBM Watson Laboratory.*—The penetration depth λ of magnetic field in a superconductor can be determined sensitively by measuring the magnetic field transmitted through a thin superconducting film if a magnetic field is applied to one side. If a field $Hz = H_0 \cos kz$ is applied (from sources at $x>0$) parallel to the film at $x=0$, the field transmitted through the film of thickness $t (t \ll \lambda)$ is $Hz = H_0(2\lambda^2 k/t)\cos kz$. The shielding factor of a film 200 A thick with $\lambda = 1000$ A and with $k = 10$ cm^{-1} is thus 1000: the magnetic field drops in 0.1 λ by a factor 2×10^3. The shielding factor is measured by varying H_0 at 10^6 cps and detecting the transmitted field by the voltage induced in a second identical space-harmonic coil, the coils being wound to have the character of a space wave-packed to allow the use of a bounded film without interference from surface currents reaching the edges. The variation of λ with T and with H (electron drift velocity) is thus readily determined, allowing a test of the nonlinear properties of superconductors. This geometry (field applied to *one side* of a thin film) allows one to separate a free-energy criterion for the critical field from the possible existence of a maximum electron drift velocity. The latter is substantiated by preliminary results (it seems reasonable on any theory involving phonons that the electrons should no longer exhibit superconductivity if they drift as fast as sound, since they can no longer be coupled toone another by phonons).

TA4. Isotope Effect in Superconducting Lead.* D. L. DECKER, D. E. MAPOTHER, AND R. W. SHAW, *University of Illinois.*—Early attempts to measure the isotope effect in Pb at temperatures below T_c were frustrated by the appearance of a strange effect which shifted the superconducting transition by amounts substantially greater than the anticipated isotope shift. Recent measurements show that the anomalous transitions always exhibit a recognizable type of irreversibility. It has also been found possible to eliminate the anomalous shift from Pb specimens by heat treatment. Measurements between about 4.2 and 1.3°K on suitably

prepared specimens show an isotope shift more nearly in harmony with results previously obtained near T_c where a shift accurately proportional to the square root of the average isotopic mass was observed.

* Work partially supported by the Office of Ordnance Research, U. S. Army.

TA5. Hysteresis Effects in the Superconducting Transition of Lead.* D. E. MAPOTHER, D. L. DECKER, AND R. W. SHAW, *University of Illinois.*—Our study of the isotope effect in superconducting Pb has made it necessary to examine some factors which affect the observed critical field. A characteristic anomaly consists of a hysteresis in the magnetic transition measured in a cycle from $S \rightarrow N \rightarrow S$. The breadth of the hysteresis may be as large as 60 gauss near 1.5°K but tends to 0 at T_c. The $S \rightarrow N$ and $N \rightarrow S$ transitions are symmetrically displaced, respectively, above and below the transition for a "normal" Pb specimen, but each transition is relatively sharp. Specimens showing the hysteresis also show microscopic traces of the superconducting phase at fields up to 100 gauss beyond the normal H_c. It has been possible to produce similar anomalies in Pb specimens by (a) straining at low temperatures, and (b) doping the specimen with Ca to produce precipitation strain. Vigorous plastic deformation at room temperature will neither produce nor remove the anomaly. It seems probable that this effect is the same as that described by Mendelssohn and McDonald.[1]

* Work partially supported by the Office of Ordnance Research, U. S. Army.

[1] D. K. C. MacDonald and K. Mendelssohn, Proc. Roy. Soc. (London) **A200**, 66 (1949).

TA6. Magnetic Field Dependence of the Surface Impedance in Superconducting Tin. M. SPIEWAK, *University of Chicago.*—The variation of the surface impedance at 1 kmc/sec is being studied as a function of magnetic field and temperature in superconducting tin. A single crystal wire is made part of a resonant cavity. Using a technique similar to Pippard,[1] the very small changes in the Q and resonant frequency of the cavity produced by the magnetic field can be measured and can be related to changes in the surface impedance. Preliminary results will be reported for the magnetic field both transverse and longitudinal with respect to the cylinder axis from 1.2°K to the transition temperature.

[1] A. B. Pippard, Proc. Roy. Soc. (London) **A191**, 370 (1947); **A203**, 111 (1950).

TA7. Superconductivity and Ferromagnetism. B. T. MATTHIAS, *Bell Telephone Laboratories.*—The compound $ZrZn_2$ has been reported by Pietrokowsky[1] as having the cubic $MgCu_2$ structure. Considering that both the constituent elements are superconductors and the average valence electron concentration is favorable to superconductivity it was a surprise to find this compound become ferromagnetic at 35°K. Until now, apart from the rare earth metals, ferromagnetism had never been found in intermetallic compounds that did not contain at least one ferro- or antiferromagnetic element. $ZrZn_2$ seems thus to be unique. It has not yet been possible to find an isomorphous compound with the same electron configuration and it is still therefore an open question how isolated this phenomenon is. Gallium is the element following zinc in the periodic system. $ZrGa_3$, the only reported compound in this system, is not isomorphous to $ZrZn_2$ and becomes superconducting at 10.5°K. No magnetic anomalies have as yet been detected among zirconium-copper compounds, copper being the element preceding zinc in the periodic system. Ferromagnetic compounds of superconducting elements might give some hope to realize Ginzburg's idea[2] of a ferromagnetic superconductor.

[1] P. Pietrokowsky, J. Metals 6, 219 (1954).
[2] V. L. Ginsburg, Zhur. Eksptl. i Teoret. Fiz. 31, 202 (1956).

TA8. Magnetic Cooling of Some Chrom-Alums.* C. F. SQUIRE AND A. THORSEN, *The Rice Institute.*—We have continued the work of Dempsey and Sapp[1] on the state of magnetization in chrom methylamine alum at very low temperatures. Using the equipment developed by Dempsey in this laboratory we have used a pressed powder specimen of the salt and find, in agreement with the single crystal studies, that there is a long relaxation time for the magnetization of the specimen when below the Néel point of antiferromagnetism. We have also examined powdered potassium chrom alum and find a rapid fall off of the susceptibility below the entropy value (0.4 R). There is no long relaxation time for magnetization below the Néel point in K Cr-alum.

* Supported by The Robert A. Welch Foundation.

[1] C. W. Dempsey and R. Sapp, Proceedings of the International Conference on Low Temperature Physics, Madison, Wisconsin (1957).

TA9. Adiabatic Cooling by Adsorbed Parahydrogen. Y. L. SANDLER, *Westinghouse Research Laboratories.*—Hindrance to rotation of hydrogen molecules in the adsorbed state is discussed. The possibility is pointed out that in some cases the lowest *ortho*-level may lie close to the lowest *para*-level. It is proposed that a simple adiabatic cooling method be obtained by allowing adsorbed parahydrogen to convert to equilibrium hydrogen at low temperatures under adiabatic conditions. Subject to certain conditions which will have to be tested experimentally, it is shown that temperatures in the neighborhood of 10^{-5} °K might be reached in a relatively simple fashion.

Invited Paper

TA10. Infrared Cyclotron-Resonance and Magneto Plasma Effects in Bismuth at Liquid-Helium Temperatures. W. S. BOYLE, *Bell Telephone Laboratories.* (30 min.)

SATURDAY MORNING AT 9:30

Mandel Hall

(R. SMOLUCHOWSKI presiding)

DSSP Symposium

Crystal Imperfections

U1. Effects of Vacancies on Physical Properties near the Melting Point. A. S. NOWICK, *IBM Watson Laboratory.* (30 min.)

U2. Motion of Radiation-Induced Defects in Copper. R. M. WALKER, *General Electric Research Laboratory.* (30 min.)

U3. Point Defects in the Noble Metals. J. S. KOEHLER, *University of Illinois.* (35 min.)

U4. Dislocations, Point-Defect-Clusters, and Cavities in LiF Crystals. J. J. GILMAN, *General Electric Research Laboratory.* (30 min.)

SATURDAY MORNING AT 11:59

Mandel Hall

(S. L. QUIMBY presiding)

Business Meeting of the Division of Solid-State Physics

SATURDAY MORNING AT 9:30

Oriental Institute

(N. BLOEMBERGEN presiding)

Paramagnetic Resonance

UA1. Spin Resonance of Mn^{2+} in NaCl at Low Concentrations. G. D. WATKINS, *General Electric Research Laboratory.*—A new spin resonance spectrum has been observed for Mn^{2+} in NaCl which is dominant at concentrations of *ca* $3(10^{-6})$ mole fraction and lower. Most crystals from several sources exhibit this spectrum with approximately the same intensity. The field splitting is large ($D \sim -500$ gauss). The spectrum is almost axially symmetric around an axis in a 100 plane which is tilted 1¼ degree away from a cubic axis. There are 12 such axes giving a complex spectrum of 12×30 lines for an arbitrary crystal orientation. This spectrum may be caused by Mn^{2+} associated with a doubly negatively charged impurity (such as $O^=$, $S^=$, etc.) substituted for the nearest halogen ion. The tilting of the axis would then be explained by a small Jahn-Teller distortion of the complex. There is no evidence of its motion up to 450°C, which is consistent with the model of association with a relatively immobile substitutional impurity. As the concentration of manganese is increased, the intensity of this spectrum remains approximately constant, and the spectra previously reported[1,2] appear and eventually dominate.

[1] E. E. Schneider and J. E. Caffyn, *Defects in Crystalline Solids* (The Physical Society, London, 1955), p. 74.
[2] G. D. Watkins and R. M. Walker, Bull. Am. Phys. Soc. Ser. II, 1, 324 (1956).

UA2. Doublets in the Electron Spin Resonance Spectrum of Mn^{++} in Calcite.* C. KIKUCHI AND R. AGER, *Engineering Research Institute, University of Michigan,* AND L. M. MATARRESE, *United States Naval Research Laboratory.*—Hurd, Sachs, and Hershberger[1] observed that some of the ESR absorption lines of Mn^{++} in a single crystal of calcite were split into doublets for certain orientations of the magnetic field with respect to the optic axis. The spectrum has been re-examined in order to check the suggestion[2] that this splitting is due to the nonequivalent trigonal fields at the two Ca^{++} sites occupied by Mn^{++} and has the dependence $\sin^3\theta \cos\theta \times \cos 3\psi$, where θ is the angle between H and the optic axis. For a given θ the doublet separation is zero or a maximum when the direction of H is varied in a plane parallel ($\cos 3\psi = 0$) or normal ($\cos 3\psi = 1$) to a symmetry plane passing through the optic axis, respectively. In the latter case the maximum splitting occurs at $\theta = 60°$ and is about 18 gauss, in good agreement with theory. In addition to the above-mentioned doublets, the spectrum contains five pairs of weak lines occurring midway between the principal hfs lines. The mechanism responsible for these lines will be discussed.

* Supported in part by the U. S. Air Force Office of Scientific Research.
[1] Hurd, Sachs, and Hershberger, Phys. Rev. **93**, 373 (1954).
[2] C. Kikuchi, Phys. Rev. **100**, 1243(A) (1955).

UA3. Spin Resonance in Electron Irradiated Silicon. G. BEMSKI, G. FEHER, AND E. GERE, *Bell Telephone Laboratories.*—An electron spin resonance line in neutron irradiated silicon has been previously reported.[1] The present work deals with centers produced by bombarding *n*-type silicon with 0.5-Mev electrons. Two sets of lines were observed at 1.2°K and at 9500 Mc/sec. The first set consisted of a central pattern which resolved into a maximum of four lines. Their positions varied as a function of the angle between the magnetic field and crystalline axes. The pattern arises from an anisotropic electronic g value and is consistent with a displacement of the Si^{29} atoms in the [100] directions. The g value of the center of gravity of this pattern equals 2.0053 ±0.0001. The second set is composed of two satellites about one order of magnitude weaker and separated by approximately 150 oe. It is assumed that these satellites are due to the hyperfine splitting of displaced Si^{29} atoms. Identical lines have been found in both bombarded phosphorus-doped and arsenic-doped silicon, but were absent in boron-doped silicon. Upon annealing a sample at 400°C for an hour the amplitudes of the bombardment induced lines have been greatly reduced.

[1] Schulz-DuBois, Nisenoff, Fan, and Lark-Horowitz, Phys. Rev. **98**, 1561(A) (1955).

UA4. Electron Spin Resonance in Nickel-Doped Germanium. G. W. Ludwig AND H. H. WOODBURY, *General Electric Research Laboratory.*—Electron spin resonance absorption (near $g = 2$) proportional in intensity to the Ni^- concentration has been detected at 14 kMc/sec in germanium crystals. These crystals contain 7×10^{15} cm^{-3} electrically active nickel atoms (introduced by diffusion at 850°C) compensated with varying concentrations of arsenic.[1] Preliminary results indicate that the symmetry of the spectrum at 21°K is interpretable in terms of centers having an anisotropic g value and a principal axis along a 110 direction. Six main lines are observed for arbitrary crystal orientation. Associated with each are ten weaker lines presumably due to hyperfine interaction with the normally 8% abundant Ge^{73} isotope (spin 9/2). A single broad line is detected at 78°K. Line widths and g values will be given.

[1] W. W. Tyler and H. H. Woodbury, Bull. Am. Phys. Soc. Ser. II, 2, 135 (1957).

UA5. Electron Spin Resonance in Germanium-Doped Quartz. JOHN H. ANDERSON,* *Mellon Institute,* AND JOHN A. WEIL, *Princeton University.*—A relatively complex set of magnetic resonance lines has been observed in a synthetic quartz crystal containing germanium (6×10^{-4} Ge/Si) which had been irradiated with x-rays. Measurements were made at room temperature with 3-cm microwaves. Six nonequivalent sets of lines, each with four components, were observed. These lines vary markedly in intensity, total width and anisotropy of g values. The range of g values is 1.992 to 2.002.

The g tensors of each set have been evaluated. The quartet structure is suggestive of hyperfine interaction, perhaps with alkali metal nuclei. The width of the individual line is about 0.2 oe. Some sets show spacings of 0.7 oe between components, whereas in others the spacing varies with angle. The lines are readily saturated at room temperature. The intensity of the paramagnetic resonance lines correlates fairly well with the intensity of an optical absorption band centered at 2700 A which has been studied by Cohen. At low temperatures, another magnetic resonance spectrum with g larger than 2.0023 occurs and is similar to the resonance studied in smoky quartz by Griffiths, Owen, and Ward, which was ascribed by them to the presence of aluminum.

* Pittsburgh Plate Glass Fellowship.

UA6. Optical and Spin Resonance Absorption in Irradiated Quartz and Fused Silica. I. Optical Absorption. C. M. NELSON AND J. H. CRAWFORD, JR., *Oak Ridge National Laboratory.**—Numerous experiments now indicate a correlation between 2150 A (C band) and the group of narrow spin resonance lines[1] observed in irradiated quartz and fused silica. Development of the C band is markedly dependent upon the previous history and type of irradiation. Co^{60} irradiations of synthetic and natural quartz indicate very little development of the C band. They do develop visible coloration and absorption below 1850 A, but some G. E. Ltd. samples do not color with Co^{60} at $>3\times10^{8}$ R. With fused silica the C band is highly developed compared with absorption below 1850 A. Development of these bands with short neutron bombardment (10^{17} fast neutrons cm^{-2}) is similar to Co^{60}. With $>10^{19}$ fast neutrons cm^{-2} quartz and fused silica have similar absorption curves. A low-temperaure neutron bombardment indicated less development of the C band in fused silica compared to absorption below 1850 A than would be expected from the 60°C bombardments. Upon annealing a Corning silica sample at 550°C, the C band disappears but some absorption below 1850 A remains. The behavior of spin resonance under identical conditions is discussed in the following paper.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] R. A. Weeks, J. Appl. Phys. **27**, 1376 (1956).

UA7. Optical and Spin Resonance Absorption in Irradiated Quartz and Fused Silica. II. Electron Spin Resonance. ROBERT A. WEEKS, *Oak Ridge National Laboratory.**—Optical absorption bands produced by gamma-ray, x-ray, and neutron irradiation of quartz and silica have been shown to arise from defects of the quartz structure and from ionization states of impurities.[1] Examination of the behavior of optical bands and spin resonance centers of specimens under a variety of experimental conditions (see preceding abstract) has established a tentative relation between an optical absorption band centered at 2150 A and the defect responsible for the spin resonance having a $g=2.0012$ in the silicas.[2] Estimates of defect concentrations in this band were made on the basis of the above assignment and comparative spin resonance measurements. The oscillator strength of the 2150 A absorption band calculated on the basis of these assumptions was $f=0.1$. By comparing annealing data on the neutron-produced spin centers in quartz with those of Mitchell and Paige on the optical behavior at wavelengths shorter than 1850 A, we find one of the spin centers is apparently related to the 1640 A (E band) optical absorption band reported by them.[1]

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] E. W. J. Mitchell and E. G. S. Paige, Phil. Mag. 1, 1085 (1956).
[2] R. A. Weeks, J. Appl. Phys. **27**, 1376 (1956).

UA8. Effect of Bleaching on F-Center Paramagnetic Resonance.* JOHN LAMBE AND JOHN A. BAKER, *University of Michigan.*—An experimental study has been carried out on the relationship between F-band optical density and paramagnetic resonance absorption as the number of F centers is reduced by bleaching. Crystals of KCl were colored by Co^{60} γ irradiation. Measurements were then made of the above quantities. F-band optical density was measured at 5460 A and F-center paramagnetic absorption was measured using an X-band magnetic resonance spectrometer. The crystals were then bleached for varying periods of time with light of wavelength 5800 A and the measurements were repeated after each bleaching. It was found that the paramagnetic absorption decreased more rapidly than the optical density. This is not in agreement with what should be expected on a simple picture of the F-band optical absorption. It indicates that either some other mechanism is operative in producing optical absorption in the F-band region, in addition to the normal F-center absorption, or that the optical properties of the F center are affected by the changes which bleaching induces.

* Supported by U. S. Air Force Office of Scientific Research.

UA9. Electron Spin Resonance in Chars of Some Simple Carbonaceous Compounds.* D. WOBSCHALL, H. AKAMATU,† AND S. MROZOWSKI, *University of Buffalo.*—The study of the paramagnetic resonance of chars obtained by heat treatment of carbonaceous substances to temperatures HT in the range 500°–1100°C was continued by using as starting materials the following compounds: C_3O_2, C_3S_2, hexamethylene tetramine (HM) and phenol-benzaldehyde (PB). The C_3O_2 char shows resonance of an extremely high intensity of 1×10^{21} spin centers per gram, the line having a very small width of 0.6 gauss. C_3S_2 chars do not show any resonance of this type. Both HM and PB chars show a resonance with a minimum line width of about 1.5 and 0.9 gauss, the PB chars showing strong saturation effects at lower heat treatments. The above results in conjunction with the previous ones (or $C_{24}H_{18}$, $C_{14}H_{10}O_2$, and $C_{14}H_{12}O$ chars[1]) demonstrate that: (1) no resonance is obtained unless the product decomposes, (2) the only element whose presence is necessary is the carbon atom, (3) presence of elements with nonzero nuclear spin broadens the line. It is concluded that the spin centers are broken carbon σ bonds.

* Work supported by the Office of Naval Research.
† On leave from University of Tokyo.
[1] Akamatu, Mrozowski, and Wobschall, *Proceedings of the Third Conference on Carbon* (Pergamon Press, New York, 1958) (to be published).

UA10. Electron Spin Resonance of Broken Carbon Bonds.* J. F. ANDREW, H. AKAMATU,† AND S. MROZOWSKI, *University of Buffalo.*—A few grains of polycrystalline graphite (soft carbon heat-treated to 2400°C in a nitrogen atmosphere) were placed in vacuum, out-gassed, and then heat-treated to over 1000°C in order to destroy the weak resonance of graphite.[1] After that they were ground mechanically *in vacuo* or in helium atmosphere at room temperature and as their size diminished electron spin resonance appeared with increasing intensity at around $g=2.007$, the line having a width of about 10 gauss, and slightly increasing with the progress of comminution. Spin concentrations of more than 10^{19} spins per gram were obtained in this manner. Admission of air kills permanently about half of this resonance absorption, the other half being somewhat weakened by the presence of oxygen (reversible oxygen effect like the one observed for chars). Heat treatment *in vacuo* to temperature of about 1000°C destroys all the resonance absorption regardless if the carbon powder *was or was not* exposed to the air after grinding. The resonance observed is probably due to broken carbon σ bonds; trapping of π electrons and forming of lone σ pairs at higher temperatures being responsible for the disappearance of resonance.

* Work supported by the Office of Naval Research.
† On leave from University of Tokyo.
[1] Hennig-Smaller effect. See G. R. Hennig and B. Smaller, *Proceedings of the First and Second Conferences on Carbon* (University of Buffalo, 1956), p. 113.

UA11. Paramagnetic Resonance Absorption in Potassium Ozonate (KO_3) and Cesium (CsO_3).* S. A. MARSHALL, D. O. VAN OSTENBURG, AND I. SIEGEL, *Armour Research Foundation.*—Magnetic susceptibility measurements reported by Kazarnovsky[1] on KO_3 show the compound to have a dipole moment of 1.67 Bohr magnetons. Paramagnetic resonance absorption measurements made at 3 cm and 1.25 cm by Bennett[2] have confirmed the paramagnetic nature of this compound. We have observed similar absorption in both KO_3 and in CsO_3. The samples are polycrystalline with purity in excess of ninety percent. At 3 cm wavelength, KO_3 shows a half-width at half-absorption of 26 oersteds and a g value of 2.008, CsO_3 shows a corresponding width of 49 oersteds and a g value of 2.006. Both absorptions are Lorentzian and the high concentration of the ozonate ion plus the apparent absence of dipolar broadening suggests the presence of exchange narrowing. Absorption line moment ratios and an analysis of the resonance line shapes add further evidence to exchange narrowing in both ozonate compounds. Using the Anderson-Weiss model for exchange narrowing we obtain exchange energies of 4×10^{-16} erg and 2×10^{-16} erg for KO_3 and CsO_2, respectively.

* This work supported in part by the Armour Research Foundation and the U. S. Army Signal Corps.

[1] Kazarnovsky, Nikolsky, and Abletsova, Doklady Akad. Nauk., S.S.S.R. **64**, 69 (1949).

[2] Bennett, Ingram, and Schonland, Proc. Phys. Soc. (London) **A69**, 556 (1956).

UA12. Paramagnetic Behavior of Copper Dihydroxydicarbonate at Low Temperatures.* R. D. SPENCE AND R. D. EWING, *Michigan State University.*—We have studied the paramagnetic behavior of $Cu_2(OH)_2(CO_3)_2$ (azurite) using the proton magnetic resonance as a probe. In the temperature range 300°K to 20°K the resonance consists of a single narrow line of anisotropic width. Below 20°K the spectrum consists of two lines whose separation increases down to about 5°K and then remains constant down to 1.8°K. At this temperature the two lines suddenly disappear and we have been unable to find the proton spectrum at lower temperatures. The temperature at which this transition takes place is slightly field dependent. We suggest that the transition is to an antiferromagnetic state.

* Sponsored by the Office of Ordnance Research, U. S. Army.

UA13. Electron Paramagnetic Resonance in Irradiated Organic Solids. R. S. ALGER, T. H. ANDERSON, AND L. A. WEBB, *U. S. Naval Radiological Defense Laboratory.*—In studying the effects of ionizing radiation on organic solids, a series of glasses and crystals composed of aliphatic molecules were irradiated and examined for electron paramagnetic resonance hyperfine structure (EPRHST). Over 40 compounds including alcohols, ethers, ketones, esters, acids, and paraffins have been irradiated and in all cases EPR species have been produced which were stable at liquid nitrogen temperature. Compounds were selected with complimentary structures of various chain lengths to permit a comparison of common features in the free radical hfs and give information regarding the range of the unpaired electrons interaction within the molecule. Most of the samples exhibited an odd number of hfs lines (3, 5, or 7) typical of an electron interacting with an even number of hydrogen atoms. A few doublets occurred in irradiated esters and acids; also a number of multiple species appeared. The maximum number of hydrogens interacting with the unpaired electron was studied in alcohol and paraffin molecules containing 4 to 11 carbon atoms in the chain. The saturation concentration of free radicals and the sensitivity of the spectrometer generally limits the observable number of lines with a binomial distribution of intensities to 7. This is the same limit given by the α-β rule[1] for a straight chain. A maximum of 9 lines was observed in isoamyl alcohol

[1] Gibson, Ingram, Symons, and Townsend, Trans. Faraday Soc. **53**, 914 (1957).

SATURDAY MORNING AT 9:30

Pathology 117

(ALBERT ROSE presiding)

Luminescence; Surface Effects

V1. Impurity Bands and Luminescence in SiC. W. J. CHOYKE AND LYLE PATRICK, *Westinghouse Research Laboratories.*—The light emitted from forward-biased p-n junctions in SiC has been measured from 77°K to 800°K. Some unusual features of the spectra can be understood by using a model of the junctions given earlier,[1] together with some conjectures on the effect of impurity banding on luminescence in solids. The light observed is partly due to impurities, partly intrinsic (transitions from conduction to valence band). The latter part has been calculated from our absorption data,[2] using the theory of van Roosbroeck and Shockley.[3] Comparison of calculated and experimental values at several temperatures involves estimates of the temperature dependence of lifetimes; nevertheless the comparison gives evidence that at 77°K electrons enter the recombination region by way of impurity bands (impurity band injection).

[1] Lyle Patrick, J. Appl. Phys. **28**, 765 (1957).
[2] W. J. Choyke and Lyle Patrick, Phys. Rev. **105**, 1721 (1957).
[3] W. van Roosbroeck and W. Shockley, Phys. Rev. **94**, 1558 (1954).

V2. Pressure Effects in Luminescence. L. REIFFEL, *Armour Research Foundation.*—In a study of the effects of hydrostatic pressure on the behavior of alkali halide phosphors, experiments have been performed using the long phosphorescence of NaI(Tl) excited by Co^{60} gammas. The behavior of a single trap is isolated by resolving the decay into exponentials assumed due to a series of first-order processes. For an isolated trap of 53-min half-life at atmospheric pressure and 40.7°C, a pressure of 30 000 psi changes the half life to 89 minutes at constant temperature. A classical theory of the effect predicts the observed linear relationship for the logarithm of the mean life ratio for pressurized and unpressurized conditions *versus* applied pressure. The change in trap depth is determined with millivolt accuracy and the critical displacement of ions required for thermal collapse of the trap may be computed if one assumes a symmetrical center with only radial oscillation modes of negative ions and negligible change in frequency factor with pressure. In the instance cited, the result is an *outward* displacement of 0.13 A. Since pressure favors smaller-than-equilibrium configurational coordinate values, these experiments can differentiate phenomena which appear indistinguishable when temperature is used as the independent parameter.

V3. Thermoluminescence Analysis of Radiation Induced Coloration in Glass. H. V. WATTS, *Armour Research Foundation.*—Presumably, the mechanism of radiation induced coloration in glass is similar to that in crystals and can be analyzed as electrons trapped in negative ion vacancies. Thermoluminescence data, "glow-curves," of gamma-irradiated crown glass, were analyzed using first-order kinetic theory to determine electron trap depths and electron frequency factors. The complex glow curve was resolved by the "saw-tooth annealing" technique and the subsequent analysis produced at least five electron trap groups. The temporal behavior of these electron traps as calculated from the thermoluminescence analysis is related to coloration fading data and phosphorescence decay data. A reasonable agreement results, thus indicating the possibility of determining time and temperature characteristics of radiation induced coloration in glass by the application of fairly simple kinetic equations to the thermoluminescence experiment.

V4. Electrical Contacts between Metals and Lead Telluride.* W. D. BRENNAN AND H. SHUCKER,† *Armour Research Foundation* (introduced by J. W. Buttrey).—The efficiency of thermoelectric refrigerators made from lead telluride type semiconductors may be greatly reduced by the resistance of contacts between the semiconductors and metals. A criterion for evaluating these contacts is developed. The resistance of contacts is measured by using a single probe to determine the potential profile of the contact. Contacts made by simple soldering, plating and soldering, and by ultrasonically agitating the solder are described; contacts made by the latter method have been made with resistances as low as 10^{-8} ohms for a one cm^2 area of contact.

* This work was supported by the National Carbon Company.
† Now at Warwick Manufacturing Company.

V5. Ohmic Probe Contacts to CdS Crystals. Y. T. SIHVONEN AND D. R. BOYD, *General Motors Corporation* (introduced by G. M. Rassweiler).—Wire probe contacts are found to be diodic upon first touching *n*-CdS, but can be permanently changed from diodic to ohmic by the passage of a moderately intense electric current pulse. This result, obtained with ten different metals, supports the idea that an exhaustion barrier exists on the surface, and contradicts proposals that ohmic contact is solely dependent upon the realtive metal and CdS work functions. It is postulated that the current pulse narrows the exhaustion barrier, thereby permitting elections to tunnel more freely and in greater numbers.

V6. Surface Properties of Cleaved Germanium Surfaces in Ultra-High Vacuum. D. R. PALMER AND C. E. DAUENBAUGH, *Honeywell Research Center* (introduced by S. Roy Morrison).—A method of obtaining "clean" germanium surfaces by cleaving germanium in ultra-high vacuum (2×10^{-9} mm Hg) has been devised. The experimental arrangement, which allows measurement of the conductance, field effect (effective mobility and slow relaxation), and photoconductivity, will be explained. A preliminary experiment on a *p*-type sample shows that the surface is *p* type upon cleavage. The effective mobility variation, upon an increase in pressure, is of the type observed in the experiments on argon bombarded surfaces.[1]

[1] P. Hander, *Semiconductor Surface Physics* (University of Pennsylvania Press, Philadelphia, 1956), Vol. 23.

V7. Surface Melt Patterns on Silicon. G. L. PEARSON AND R. G. TREUTING, *Bell Telephone Laboratories, Inc.*—Surface melt patterns have been formed on silicon by heating to within a few degrees of the melting point (1412°C), followed by a rapid quench. This is most easily accomplished by flashing an electric current through an oriented single crystal rod in air at atmospheric pressure. Localized melting occurs where specks of impurities reside on the surface. Surface tension draws the molten silicon into small hemispheres and the close-packed {111} planes, to which the silicon atoms are most tightly bound, are revealed. Straight-sided geometrical patterns several microns in extent are thus formed and their shapes are uniquely determined by the surface crystal plane. These patterns are squares on a {100} crystal surface, equilateral triangles on a {111}, isosceles triangles on a {211} and parallel striations on a {110} crystal surface. Conclusive proof that these melt patterns are determined by {111} planes rather than any other system has been obtained through a study of their shapes on rational crystal surfaces presented by multitwinned crystals. We have formed similar patterns on germanium, indium antimonide,[1] gallium antimonide, and gallium arsenide crystals using this technique.

[1] M. F. Millea and C. T. Tomizuka, J. Appl. Phys. **27**, 96 (1956).

V8. Barrier-Height Measurement by Means of Surface Capacitance. H. M. BATH AND M. CUTLER, *Hughes Products.*—A bridge technique is used to measure small changes in C, a series combination consisting of a capacitance C_s associated with a semiconductor surface barrier, and C_x, supplied by a plate parallel to the surface under investigation. When a dc voltage, V, is applied to the external plate, a charge is induced into the semiconductor, changing C_s and thence C. From a series of measurements of ΔC as a function of various values of V, one may calculate the change in surface potential from its initial value to be $\Delta\phi_s(V)=\int_0^V C_x C_s^{-1}(V')dV'$. Such a computation of $\Delta\phi_s$ from capacitance measurements is free of the assumptions about surface mobility which are necessary if it is to be determined from measurements of conductance change. As with any field-effect measurement, rates of charge and discharge of slow surface-states can be observed. Experimental and theoretical aspects of the measurement are discussed, as well as typical results obtained with germanium.

V9. Field Effect on Silicon.* T. C. HALL AND M. F. MILLEA *Pacific Semiconductors, Inc.*—Field effect experiments have been undertaken on *n*-type silicon to evaluate the characteristics of various chemical surface structures. The experimental apparatus is similar to that of Montgomery and Brown[1] except that Mylar has been used as the dielectric spacer. The maximum induced charge is 4×10^{11} charges/cm^2. With a square wave applied to the field plate, a conductivity decay process (time constant$\sim$0.01 sec) appears on the negative cycle. The time constant is found to increase with field plate voltage. Due to this decay process, the $\Delta\sigma$ *vs* Q oscilloscope trace shows hysteresis at frequencies between 10 and 10^3 cps, becoming more pronounced when the field plate is negative. No hysteresis is observed at 3 cps. As the field plate is driven strongly negative, the expected minimum conductance is not observed. Low intensity light on the specimen is found to eliminate hysteresis and allows a minimum conductance to be observed. At higher light intensities the position of the minimum is shifted. A model to account for these observations and the effects of various surface treatments will be discussed.

* This work was supported by contract with the United States Army Signal Engineering Laboratories.
[1] H. C. Montgomery and W. L. Brown, Phys. Rev. **103**, 865 (1956).

V10. (Abstract withdrawn.)

Invited Paper

V11. Recent Advances in the Understanding of Semiconductor Surfaces. HERMANN STATZ, *Raytheon.* (30 min.)

SATURDAY MORNING AT 9:30

Kent 107

(J. R. PLATT presiding)

DCP Symposium

The Many-Body Problem

VA1. Theory of Phase Transitions through Machine Calculations. BERNARD ALDER, *Radiation Laboratory, University of California.* (40 min.)

VA2. Quantum Statistics of Interacting Particles. E. W. MONTROLL, *Institute for Fluid Dynamics and Applied Mathematics, University of Maryland.* (40 min.)

VA3. Recent Progress in the Theory of the Electron Gas. KEITH BRUECKNER, *University of Pennsylvania.* (40 min.)

VA4. Low-Temperature Properties of a Hard Sphere Boson Gas. KERSON HUANG, *Massachusetts Institute of Technology.* (40 min.)

SATURDAY AFTERNOON AT 2:00

Kent 106

(R. S. MULLIKEN presiding)

Chemical Physics

W1. Correlated Wave Function for the Ground State of Helium-Like Systems.*† C. C. J. ROOTHAAN, *University of Chicago.*‡—The ground state of a helium-like system is represented by a wave function of the form $\psi(r_1)\psi(r_2)\chi(r_{12})$, where ψ and χ are functions to be determined by minimizing the energy. Unlike many other approximate wave functions, a wave function of this form has the proper singularities for $r_1 \to 0$, $r_2 \to 0$, $r_{12} \to 0$ if ψ and χ have the right slopes at these points. An actual calculation was done for the helium atom. Simple expansions in terms of polynomials and exponentials were put forward for ψ and χ, and the energy was minimized with respect to the coefficients and exponents. The resulting wave function accounts for 92% of the correlation energy.

* Work assisted in part by the Office of Naval Research, U. S. Air Force, Office of Scientific Research, and the National Science Foundation.

† A preliminary version of this paper was presented at the Symposium on Molecular Quantum Mechanics in Paris, September 30-October 5, 1957.

‡ Paper prepared when the author was with the Department of Theoretical Chemistry, Cambridge University, under the auspices of a Guggenheim Fellowship.

W2. Molecular Orbital Calculations for Excited States of H_2. PAUL E. PHILLIPSON AND R. S. MULLIKEN, *The University of Chicago.*—Usual LCAO-MO calculations on low excited states of molecules involving configurations $\cdots\Phi_B\Phi_A$ give too large singlet-triplet energy separations $E_S - E_T$. For H_2 the molecule, where Φ_B, Φ_A are of the forms $1s_a, 1s_a = 1s_a \pm 1s_b$ (unnormalized) with $1s = e^{-\zeta r}$, the computed $E_S - E_T$ is 6.0 ev at the ground-state equilibrium interatomic distance ($r_{ab} = 0.74$ A), for $\zeta = 1$.* Adjustment of ζ improves E_S and E_T, but hitherto such adjustment has been confined to use of the same ζ for $1s_g$ and $1s_u$. The present treatment employs different ζ's (ζ_g and ζ_u) for the $1s_g$ and $1s_u$ orbitals. With $(\zeta_g, \zeta_u) = (1.325, 0.575)$ for the triplet, and (1.325,0.500) for the singlet, we find $E_S - E_T = 3.9$ ev at $r_{ab} = 0.74$ A. These computations are being extended for other r_{ab} values out to ∞ (where the singlet must be an ion pair with $\zeta_g = \zeta_u = 0.7$, and the triplet, an atom pair with $\zeta_g = \zeta_u = 1$). A similar procedure will be applied to ethylene, where $\Phi_B, \Phi_A = 2p_{x_a} \pm 2p_{x_b}$, $2p_x = xe^{-\zeta r}$. In this case $\zeta_g = \zeta_u = 3.25$ gives $E_S - E_T = 8$ ev as compared to the observed 1.2 ev.

* The singlet and triplet wave functions are given by ${}^{1,3}\Sigma_u^+ = [\sigma_g(1)\sigma_u(2) \pm \sigma_g(2)\sigma_u(1)]$.

W3. Computation of Electronic Properties of First-Row Diatomic Molecules by Digital Computer.* A. D. MCLEAN, P. I. MERRYMAN,† B. J. RANSIL, J. W. RICHARDSON,† C. C. J. ROOTHAAN, K. RUEDENBERG,† A. WEISS, AND M. YOSHIMINE, *University of Chicago.*—Programs for computing all necessary one- and two-center integrals involving Slater-type atomic orbitals (AO's) for quantum numbers $n = 1,2$ ($n = 3$ in the case of

the one-electron integrals) have been written for the Scientific Univac and are now operating. Programs for the calculation of certain types of three-center integrals for almost any n, but for a maximum l of 7 are also operating. Description and discussion of results for the various integral programs will be given. An SCF procedure for computation of LCAO molecular orbitals has been programed and is operating. This, coupled with the integral programs, provides a complete computational tool for the determination of "best-LCAO-MO" eigenfunctions (obtained by varying the exponents of the atomic orbitals and the coefficients of the LCAO-MO's) for ground and excited states of first-row homopolar, heteropolar, and hydride molecules. From these eigenfunctions (further improved by configuration interaction), calculation of molecular energies and other properties can be computed. Initial results will be discussed.

* Work assisted by the Office of Naval Research, U. S. Air Force Office of Scientific Research, and the National Science Foundation.
† J. W. Richardson is now at Purdue University; K. Ruedenberg is now at Iowa State College, P. I. Merryman is now at RIAS, Inc., Baltimore, Maryland.

W4. Simplified Derivation of the Binary Collision Expansion and Its Connection with the Scattering Operator Expansion.* A. J. F. SIEGERT AND EI TERAMOTO, *Northwestern University.*—The binary collision expansion for the density matrix of a system of N particles with pair interaction was derived by Huang, Lee, and Yang[1,2] by expansion in the interaction and subsequent summation over terms represented by certain classes of diagrams. A simpler derivation has been obtained by the use of the $N(N-1)/2$ integral equations which relate the density matrix of the system to the density matrices of systems in which only one pair of particles interacts. Successive substitution of the integral equations into each other yields an expansion which by a trivial additional step becomes the binary collision expansion. Our derivation shows also that the binary collision expansion is the Laplace inverse of the coordinate representation of the expansion in terms of scattering operators.[3]

* Work supported by the National Science Foundation.
[1] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1119 (1957).
[2] Huang, Lee, and Yang, preprint "Quantum Mechanical Many-Body Problem and the Low-Temperature Properties of a Bose Gas of Hard Spheres" (Lecture of C. N. Yang at the Stevens Conference, January, 1957).
[3] K. Watson, Phys. Rev. **103**, 489 (1956).

W5. One-Dimensional Inelastic Collisions with Impulsive Interactions.* B. WIDOM, *Cornell University.*—If a linear oscillator interacts impulsively with a mass incident along its line of oscillation, then the probability p_{mn} of the oscillator undergoing the change in state $m \to n$ due to the collision may be obtained directly from the coefficients of an expansion in a series of nonorthogonal functions. In the limit in which the mass of the impinging particle $\to 0$ and its energy $\to \infty$, but its momentum remains positive and finite, one obtains simply $p_{mn} = |e_{nm}|^2$, where e_{nm} is the n,m matrix element of $\exp(-2ikx)$ calculated with unperturbed oscillator wave functions, k being the initial wave number of the incident mass and x being the oscillator coordinate. Explicit results are quoted for the linear string oscillator, which is mechanically equivalent to a particle in a one-dimensional box. The possibility of obtaining explicit results in the more general case of nonzero mass and finite energy of the impinging particle is also discussed.

* Work supported by U. S. Air Force Office of Scientific Research.

W6. Redundant Coordinate Problem in the Rotational-Vibrational Spectra of Polyatomic Molecules. RAYMOND GOLD, JEROME M. DOWLING, AND ARNOLD G. MEISTER, *Illinois Institute of Technology.*—A consistent method is described for treating redundant coordinates in the Wilson treatment of the rotational-vibrational problem of polyatomic molecules. This method furnishes a unique set of potential energy constants for molecules having redundant internal coordinates. Techniques are developed which permit the caluclation of the rotational distortion constants by use of the internal coordinates. A method is given for obtaining the partial derivatives of the moment of inertia tensor with respect to the internal coordinates which is applicable even when redundant coordinates are present. The results for a ZX_3Y molecule are tabulated in matrix form.

W7. Infrared Spectral Data and Assignments for $CHCl_2F$ and $CHClF_2$ and Potential Energy Constants and Calculated Thermodynamic Properties for $CHCl_2F$, $CDCl_2F$, $CHClF_2$, and $CDClF_2$. HERMAN B. WEISSMAN, ARNOLD G. MEISTER, AND FORREST F. CLEVELAND, *Illinois Institute of Technology.*—Infrared spectral data were obtained with NaCl and CsBr prisms for gaseous $CHCl_2F$ and $CHClF_2$ from 270 to 4000 K (K = kayser = wave/cm) and the observed absorption bands were assigned to the vibrational modes for both molecules. Using the Wilson FG matrix method, reasonable values of the F-matrix elements were found which reproduced the observed wave numbers to within 2%. From these F-matrix elements and analytical expressions obtained from the theory of Gold, Dowling, and Meister, the f-matrix elements (potential energy constants) were obtained. These matrix elements were then used to calculate the wave numbers corresponding to the fundamental vibrations of $CDCl_2F$ and $CDClF_2$. Having tested the assignments by the normal coordinate treatment, the observed wave numbers for $CHCl_2F$ and $CHClF_2$ were then used to calculate the enthalpy function, the free energy function, the entropy, and the heat capacity for 1 atmos pressure and for 12 temperatures from 100 to 1000°K—to a rigid rotor, harmonic oscillator, ideal gas approximation. Since the calculated wave numbers for $CDCl_2F$ and $CDClF_2$ should be reliable within about 2%, these were used in similar thermodynamical calculations to establish tentative values of the thermodynamic functions for these molecules.

W8. Raman and Infrared Spectra of $C_2H_2Br_4$ and $C_2D_2Br_4$. S. SUNDARAM, E. A. PIOTROWSKI, S. I. MILLER, AND FORREST F. CLEVELAND, *Illinois Institute of Technology.*—A study of the Raman and infrared spectra of substituted ethanes is of special interest in relation to rotational isomerism. The existence of two forms, *trans* and *gauche*, has been inferred by various workers from a study of these spectra. Kagarise[1] has made a partial assignment of the observed fundamentals for $Br_2HC\text{-}CHBr_2$. In the present investigation, the wave numbers, relative intensities, and depolarization factors of the lines in the Raman spectra of both $Br_2HC\text{-}CHBr_2$ and $Br_2DC\text{-}CDBr_2$ have been determined. Also, the Raman spectra have been recorded at various temperatures so that assignments could be made for the isomeric forms present. In addition, the infrared spectra of the two compounds have been obtained in the range 400 to 4000 K (K = kayser = wave/cm). The Raman and infrared spectral data have been compared to arrive at a complete assignment of the observed bands. A normal coordinate treatment, which will provide a check on the assignment, is also in progress.

[1] R. E. Kagarise, J. Chem. Phys. **24**, 300 (1956).

W9. Mass Spectrometric Study of Inter-Group IVB Molecules. G. DE MARIA, J. DROWART,* AND M. G. INGHRAM, *University of Chicago.*—As part of a study of gaseous carbides, SiC and Ge have been vaporized from graphite crucibles at pressures between 10^{-4} and 10^{-1} mm Hg at temperatures between 1500 and 2200°K. The predominant gaseous carbides are SiC_2 and Si_2C above SiC, and Ge_2C above Ge+C. Dissociation energies have been computed using measured partial pressures and estimated electronic vibrational, and rotational partition functions. The vibrational frequencies

used for the SiC_2 molecule are those recently reported by B. Kleman,[1] whereas for Si_2C and Ge_2C they were estimated by analogy with those for SiC_2. The results are $D_0(Si-C_2)=7.2\pm0.5$ ev, $D_0(Si_2-C)=7.2\pm0.6$ ev, and $D_0(Ge_2-C)=6.8\pm0.3$ ev. These dissociation energies will be discussed in comparison with known dissociation energies of C_2, C_3, Si_2, Si_3, Ge_2, and Ge_3.

* On leave of absence from Université Libre de Bruxelles, Brussels, Belgium.

[1] B. Kleman, Astrophys. J. **123**, 162 (1956).

SATURDAY AFTERNOON AT 1:30

Mandel Hall

(J. G. DAUNT presiding)

DSSP Symposium

Magnetism at Very Low Temperatures

X1. Studies in Magnetism and Thermometry at Low Temperatures. R. P. HUDSON, *National Bureau of Standards.* (30 min.)

X2. Thermal and Magnetic Properties of Several Rare Earth Ethylsulfates at Very Low Temperatures. HORST MEYER, *Harvard University.* (30 min.)

X3. Properties of Magnetically Anisotropic Crystals below 1°K. J. C. WHEATLEY, *University of Illinois.* (30 min.)

X4. A Two-Stage Magnetic Refrigerator. H. B. SILSBEE, *University of California.* (30 min.)

SATURDAY AFTERNOON AT 1:45

Pathology 117

(C. G. SHULL presiding)

Irradiation Effects, II

XA1. Studies of Damage in Semiconductors Caused by Various Nuclear Particles.* J. J. LOFERSKI AND P. RAPPAPORT, *RCA Laboratories.*—The short circuit current, I_s, produced by ionizing radiation near a p-n junction is proportional to the square root of the minority carrier lifetime, τ. Changes in τ produced by energetic penetrating radiation can be followed by observing corresponding changes in I_s. We have previously described experiments in which β particles produced both the ionization and the damage.[1] In this paper we shall discuss experiments in which the ionizing radiation differs from the damage-producing radiation. In one case, the damage caused in Ge by neutrons in a reactor was observed through the voltaic effect produced by the γ rays in the reactor. In a second case, I_s produced by an intense light was used to observe damage in Si caused by α and β particles and protons. This method is especially attractive because it allows observations to be made on junctions with very low initial values of τ. The decay rates produced by these radiations are proportional to the product of defect concentration, N_r and the cross section for capture of minority carriers, Σ_c. Experimental and theoretical ratios of $N_r\Sigma_c$ for the different radiations used will be compared.

* This work sponsored partly by the U. S. Signal Engineering Laboratories.

[1] J. J. Loferski and P. Rappaport, Phys. Rev. **98**, 1869 (1955).

XA2. Electron Irradiation Induced Lifetime Changes in Ge as a Function of Conductivity. P. RAPPAPORT AND J. J. LOFERSKI, *RCA Laboratories.*—High-energy irradiation introduces recombination centers into Ge, which reduce the minority carrier lifetime, τ. If these centers are all located at a single energy level, E_t, in the forbidden energy gap, their effectiveness as recombination sites will be a function of E_F-E_t, where E_F is the Fermi level in the material. Consequently, the rate of change of τ during irradiation will depend on E_F.[1] We have tested this hypothesis by observing the rate of decay of τ in Ge wafers for eight values of E_F (2×10^{13}/cc $<|N_D-N_A|<2\times10^{14}$/cc) in n-type material and an equal number in p-type material. A 1-Mev Van de Graaff accelerator supplied the electrons used in this study. The integrated flux was too low to permit any radiation induced changes in conductivity. Plots of the rate of decay of τ vs E_F pass through a minimum when E_F is near the center of the gap, in agreement with theory. The decrease of τ is compared to the corresponding decrease in I_s, the radiation produced minority carrier current in a p-n junction. Differences between their behavior near the intrinsic region will be discussed.

[1] J. J. Loferski and P. Rappaport, Phys. Rev. **98**, 1869 (1955).

XA3. Electron Irradiation of Ge between 5 and 300 kev.* W. E. SPEAR, J. W. MACKAY, E. E. KLONTZ, and K. LARK-HOROVITZ, *Purdue University.*—It is shown that irradiation with electrons, having energies as low as 5 kev, produces significant changes both in the photoconductive response and the conductivity of n- and p-type Ge at 80°K. The changes anneal out completely when the specimens are warmed to room temperature. Experiments with different surface treatments and with samples of different thickness indicate that the photoconductive "shoulder" observed before irradiation in the 1.8- to 2.2-μ region is connected with a surface effect. Moreover, electron irradiation with energies from 5 kev to 300 kev is found to be almost equally effective in quenching

the response in the above spectral range. This effect is closely connected with changes in surface conductance which, on irradiation, increases in n-type and decreases in p-type material. The results show that the observed effects depend on the ionization produced in the surface region. Low-energy irradiations have also been used in conjunction with 4.5 Mev irradiations in an attempt to isolate that part of the photoconductive response which is introduced by volume defects.

* Supported by a U. S. Atomic Energy Commission contract.

XA4. Effect of Surface Preparation on the Electrical Properties of Irradiated Germanium.* J. KORTRIGHT AND J. MACKAY, *Purdue University* (introduced by K. Lark-Horovitz).—n-type germanium single crystals (ρ at 300 K ~11–15 ohm cm) have been irradiated at 80°K with electrons of energies less than 500 kev. Specimens of 100-μ thickness were oriented with the 110-direction parallel to the incident beam. Measurements of the Hall coefficient R and conductivity σ were made. Surface preparation had a marked effect on irradiation-induced changes in R and σ. A comparison was made between specimens which had been polished or etched with various solutions. Generally $1/R$ and σ increased upon initial irradiation, then decreased linearly at a slower rate upon further irradiation. The magnitude of these changes depended on the surface treatment. As these surface effects occur for irradiation energies in the region of the threshold energy for bulk damage, it is evident that any threshold determination must take them into account.

* Supported by a U. S. Atomic Energy Comission contract.

XA5. Energy Levels Introduced into Silicon by Electron Irradiation.* D. E. HILL AND K. LARK-HOROVITZ, *Purdue University*.—The effect of electron irradiation on the electrical properties of single crystal silicon samples has been investigated with electrons of several different energies. Hall effect and resistivity have been measured as a function of temperature at various stages of the bombardment. Irradiation at 4.5 Mev indicates that the bombardment levels which are introduced at the highest rate are close to the band edges. Deeper lying levels are introduced at comparatively low rates. Irradiations at 0.3, 0.7,† and 4.5 Mev on n-type material indicate a level, 0.17 ev from the conduction band, which removes conduction electrons whith low introduction rates. A similar level with a still lower introduction rate was observed in the neighborhood of 0.4 ev from the conduction band when 0.7- and 4.5-Mev electrons were used. A p-type sample irradiated at 0.7 Mev shows evidence for a level at about 0.3 ev from the valence band with low introduction rate.

* Work supported by a U. S. Atomic Energy Commission contract.
† At 0.7 Mev similar results have been reported by G. K. Wertheim [Phys. Rev. **105**, 1730 (1957)].

XA6. Neutron Bombardment Damage in Silicon.* G. K. WERTHEIM, *Bell Telephone Laboratories*.—Fast neutron damage in silicon may be interpreted in terms of the damage produced by 1.0-Mev electrons which produce two discrete energy levels in the forbidden gap. A discrete acceptor level 0.27 ev above the valence band is produced by both electrons and neutrons. In the electron case this level has been identified with a damage site containing two well-separated point imperfections. A donor level is found extending from 0.16 ev below the conduction band toward the middle of the gap. This level is related to a discrete one produced by electron bombardment which was identified with a close-spaced pair of defects. The broadening of the level in the neutron case is ascribed to the production of a spectrum of spacings ranging upward from the minimum value of 2.5 A found after electron bombardment. The lifetime in neutron bombarded samples is grossly different from that obtained in electron bombarded crystals. The results are not compatible with a single recombination center, suggesting rather, the agency of a spectrum of levels close to the center of the gap, probably associated with the broadened 0.16-ev level. Mobility measurements indicate the presence of further charged sites.

* This work was supported in part by the Wright Air Development Center of the U. S. Air Force.

XA7. Surface Sensitive Conductance of High-Resistivity Silicon.* E. Y. WANG AND T. A. LONGO, *Purdue University*.—Nonequilibrium effects have been observed in the electrical properties of high-resistivity silicon after deuteron irradiation at room temperature. After the deuteron beam is turned off, the conductivity decreases and the Hall coefficient increases, i.e., in the direction continued irradiation would have driven them. This decay of excess conductance lasts for hours and is most pronounced in n-type samples. The condition of nonequilibrium could be restored by ultraviolet illumination. Similar effects have been investigated in unirradiated gold doped n-type silicon from Texas Instruments. The proper conditions for observation appear to be very high resistivity and oxidizing surface treatment. The most sensitive excess conductance effect, retained after ultraviolet illumination has been found in samples etched with CP_4 and later treated with $KMnO_4$. The conductance of such samples has also been found to be very sensitive to ambient. The dark conductance and the sensitivity to ultraviolet illumination is considerably higher in vacuum than in air. Field-effect experiments indicate n-type surfaces in these samples. Ultraviolet illumination makes the surface more n type. HF etch reduces the dark conductance considerably and removes most of the sensitivity to illumination.

* Supported by a U. S. Signal Corps contract.

XA8. Radiation Effects in Indium Arsenide. J. W. CLELAND AND J. H. CRAWFORD, JR., *Oak Ridge National Laboratory*.*—Polycrystalline n- and p-type plates of the semiconducting intermetallic compound InAs[1] have been irradiated in the Oak Ridge National Laboratory Graphite Reactor. The samples were shielded from thermal energy neutrons by In and Cd foils to eliminate largely the introduction of chemical impurities by transmutation processes. The carrier concentration and conductivity of n-type material increased under fast neutron irradiation, indicating that the lattice damage resulting from bombardment serves primarily to introduce donor centers. A total exposure of 2×10^{17} fast neutrons/cm^2 resulted in the apparent addition of approximately 2×10^{17} current carriers/cm^3 as determined by subsequent Hall coefficient measurements. The conductivity of p-type material decreased to an apparent minimum and then increased in a manner analogous to n-type material. Subsequent Hall coefficient measurements indicated a conversion from p-type to n-type material. The total current carrier concentration change was again fairly equivalent to the total integrated fast flux. Moderate temperature (100°C) anneals indicate that the radiation produced current carrier concentration changes are stable to at least this temperature.

* Oak Ridge National Laboratory is operated by Union Carbide Nuclear Company for the U. S. Atomic Energy Commission.
[1] The samples were kindly supplied by D. P. Enright of the Naval Ordnance Laboratory.

XA9. Gamma Irradiation of InSb. CHARLES R. WHITSETT, *National Carbon Research Laboratories*.—Hall coefficients and resistivities of n- and p-type single crystals of InSb immersed in liquid nitrogen were measured at intervals during a 48-hr period of exposure to 2.1×10^6 r/hr Co^{60} gamma irradiation. Measurements also were made during a subsequent 500-hr anneal at 77°K. Before irradiation the n-type InSb at 77°K had $n=7.1\times10^{14}$ cm^{-3} and $\mu_n=320\,000$ cm^2/volt sec; the p-type InSb at 77°K had $p=5.6\times10^{13}$ cm^{-3} and $\mu_p=10\,300$ cm^2/volt sec. Irradiation of the n-type sample removed 7.0×10^{12} conduction electrons/cm^3 hr (0.02 electron/cm^3 per incident photon); no annealing of the damage at 77°K was

detectable. Irradiation of the p-type sample introduced 2.8×10^{12} holes/cm^3 hr (0.009 per photon). The annealing afterwards followed a bimolecular recombination law with the fraction of defect induced holes annealed after t hours being given by $\phi=1/(1+5.9\times10^{16}/p_0t)$ (p_0=initial number of defect induced holes/cm^3). An observed decline of the rate of hole production in p-type InSb may be explained by irradiation enhanced annealing. If two electron traps are induced per absorbed photon, the cross section for defect production by 1.3 Mev gammas in InSb is 4×10^{-25} cm^2.

XA10. Na Nuclear Magnetic Resonance in Proton Irradiated NaCl.* KOICHI KOBAYASHI,† W. I. GOLDBURG, AND R. T. SCHUMACHER, *Carnegie Institute of Technology.*—The line shape of the Na nuclear resonance in NaCl crystals upon irradiation with 350 Mev protons with a total flux of 10^{16} protons/cm^3 has been studied as a function of annealing temperatures. It was found that the total intensity of the resonance was unaffected by the irradiation, and that the intensity of the resonance remained constant during the entire annealing process. Significant line shape changes were noted, however, both between irradiated and unirradiated crystals, and as a function of annealing temperature. The change of line shape is qualitatively as predicted by Cohen and Reif for charged point defects of low concentration, and the increase in line width is qualitatively in agreement with the increase expected from the number of defects found to be present in previous measurements[1] by other techniques. In addition, the line width as a function of temperature is in qualitative agreement with the density measurements; it shows the same independence of annealing temperature between room temperature and 200°C and the recovery of the original line width is complete at 400°C.

* Work supported by a U. S. Atomic Energy Commission contract.
† Now at the University of Illinois.
[1] K. Kobayashi, Phys. Rev. **107**, 41 (1957).

XA11. Measurement of Irradiation-Induced Expansion of Alkali Halides by Photo-Elastic Methods.* R. SMOLUCHOWSKI AND D. A. WIEGAND, *Carnegie Institute of Technology.*—A modification of the photo-elastic method of Primak, Delbecq, and Yuster has been used to study the irradiation induced volume expansion of alkali halide crystals. One-half of a rectangular plate is irradiated in a direction normal to the surface of the plate in such a manner as to produce throughout it electronic ionization, while the other half is shielded from the radiation. The constraint placed upon the irradiated portion of the crystal by the unirradiated portion at the boundary hampers the expansion of the irradiated part and so introduces strain into both halves of the crystal. The crystal becomes birefringent and the strain pattern can be analyzed by the use of polarized light. With the additional knowledge of the photoelastic constant, the volume expansion of the irradiated portion can then be calculated. This method has the advantage over other techniques such as density changes or dimensional change that it can be easily used over a large temperature range. Curves of expansion *vs* time of x-ray irradiation of LiF determined by this method will be compared with the expansion calculated from color center measurements.

* Work supported by a U. S. Atomic Energy Commission contract.

XA12. Irradiation-Induced Expansion and Annealing of LiF at Low Temperatures.* D. A. WIEGAND AND R. SMOLUCHOWSKI, *Carnegie Institute of Technology.*—By photoelastic techniques described in the previous abstract the volume expansion of LiF due to x-ray irradiation at low temperature has been measured and compared with room-temperature expansion. At −180°C the expansion increases linearly with x-ray dose for fractional volume change of 10^{-3} to 10^{-4}, while at 25°C a saturation type of growth curve is found. Approximately 70% of the volume expansion caused by irradiation at −180°C anneals out when the crystal is warmed to −130°C, but further warming to room temperature produces little additional change. The expansion remaining at room temperature is roughly equal to that introduced into a fresh crystal by an equal amount of irradiation at room temperature. The F-center density decreases by about 30% in warming a crystal irradiated at −180°C to −130°C and an absorption band at 3400 A anneals completely. However, while the F band and the volume expansion increase linearly with flux at −180°C the band at 3400 A saturates, indicating that it may be due to an impurity. The dependence of these effects on plastic deformation will be discussed.

* Work supported by a U. S. Atomic Energy Commission contract.

XA13. Isothermal Changes of Ionic Conductivity of Gamma-Irradiated NaCl in the Temperature Range 65–80°C.* H. S. INGHAM, JR., AND R. SMOLUCHOWSKI, *Carnegie Institute of Technology.*—Single crystals of NaCl were subjected to about 10^5 roentgens of gamma irradiation from Co^{60}, at 5°C, and then rapidly heated and maintained at a fixed temperature in range 65–80°C. The dc ionic conductivity at this temperature was measured as a function of time using a vibrating reed electrometer. The conductivity decreased during a period of several hours to a value that was less than the preirradiation conductivity by a factor of about 30. This is in agreement with previous nonisothermal annealing studies.[1] The conductivity is presumed to be a direct measure of a change in the number of positive ion vacancies. The data fit a rate equation describing the bimolecular process $A+B\rightarrow AB$, with an activation energy approximately equal to that of the mobility of the positive ion vacancies. This seems to confirm the supposition that the change of conductivity reflects the clustering of the positive ion vacancies with other imperfections at a rate controlled by the diffusion of these vacancies.

* Work supported by a U. S. Atomic Energy Commission contract.
[1] E. A. Pearlstein, Phys. Rev. **92**, 881 (1953); K. Kobayashi, Phys. Rev. **102**, 348 (1956).

SATURDAY AFTERNOON AT 1:30

Oriental Institute

(R. E. NORBERG presiding)

Ferromagnetic and Nuclear Magnetic Resonance

Y1. Proton Magnetic Resonance of Magnetically Dilute Silica-Aluminas and Silica Gels. D. E. O'REILLY, *Gulf Research & Development Company.*—Lorentzian line shapes have been found for the proton magnetic resonance of highly dehydrated (500°C), high surface area silica-alumina (12.5 wt % Al_2O_3) (SA) and silica gel (SG) powders by CW

methods.[1] The line shape and widths (100 to 310 milligauss) are independent of temperature between −210° and 280°C. Deuterium exchange with D_2 at 350°C or D_2O at 150°C results in a decrease in width without change in line shape. These results appear consistent with the Kittel-Abrahams theory of magnetically dilute systems.[2] The chemical shift of the protons relative to water is -0.3×10^{-6} (to higher field). Over the concentration range of 3×10^{19} to 6×10^{20} proton g^{-1}, the proton integrated intensity is nearly a linear function of the nitrogen (BET) surface area (4 to 425 m^2g^{-1}) for SA. Spin-lattice relaxation times range from 40 milliseconds to several seconds for magnetic impurity (mainly Fe^{+3}, Cr^{+3}) contents of 500 to 10 ppm. Dispersion mode derivatives are found to saturate at rf fields about 10 times those required for saturation of the absorption mode for T_1 values near 0.1 sec.

[1] O'Reilly, Leftin, and Hall, J. Chem. Phys. (to be published).
[2] C. Kittel and E. Abrahams, Phys. Rev. **90**, 238 (1953).

Y2. Pure Quadrupole Resonance in Electron- and Gamma-Irradiated Paradichlorobenzene.* R. S. POWELL, *General Electric Research Laboratory*, AND R. M. LICHTENSTEIN, *Rensselaer Polytechnic Institute*.—The effects of 800 KVP electrons and Co-60 gamma rays on the quadrupole resonance of Cl^{35} in $p-C_6H_4Cl_2$ have been studied at room temperature with a Zeeman-modulated superregenerative rf spectrometer. No frequency shift was observed. Electron irradiation at a rate of 1.4 megaroentgens/min, decreases the resonance intensity with increasing dose R in megaroentgens according to the relation $\ln I_0/I_b=-0.068\,R$, where I_b is the intensity before irradiation, and I_0 is the intensity immediately following irradiation. The intensity recovers exponentially with time, sometimes fully, sometimes partially to a plateau. The time constant of this recovery is approximately 70 min. (Decay of paramagnetic resonance in electron-irradiated samples proceeds exponentially at about the same rate.) Samples irradiated with gamma rays at a rate of 0.22 megaroentgen/hr showed only a "nonrecoverable" decrease in the resonance intensity of the order of 10% for a dose of 64 megaroentgens. "Recoverable" damage, if any, in the gamma-ray case is believed to recover simultaneously with long exposure period (days) and is therefore unobserved. The short irradiation time (min) possible with electrons permits observation of rapid recovery effects.

* Part of an M. S. thesis submitted by one of us (RSP) to R.P.I., January, 1958.

Y3. NMR Acoustic Absorption in KI and Br. D. I. BOLEF, *Westinghouse Research Laboratories*, AND M. MENES, *University of Pittsburgh*.—Nuclear magnetic resonance acoustic absorption[1] of I^{127} in KI and of Br^{79} and Br^{81} in KBr has been observed at 8 Mc and 10 Mc, respectively. The sound was propagated along a [100] axis of the crystal. Absorption lines corresponding to "double-frequency" transitions ($\Delta m=\pm2$) have a cyclic angular distribution of intensity sharply peaked at $\theta=90°$ and 270°, where θ is the angle between the [100] axis and the external magnetic field. The "normal" resonance lines ($\Delta m=\pm1$) have a doubly cyclic angular distribution with sharp minima at $\theta=0°$, 90°, 180°, and 270°. The line widths are of the order of several gauss. Relative intensities of the I and Br nuclear resonances are consistent with a quadrupolar coupling to the spin system. The departure of the angular distribution of intensity from that predicted by quadrupolar transition probabilities can be related to the effects of static quadrupole interactions due to the strains in the crystals.[2]

[1] M. Menes and D. I. Bolef, Phys. Rev. **109**, 218(L) (1958).
[2] J. F. Hon and P. F. Bray, Bull. Am. Phys. Soc. Ser. II, **3**, 22 (1958).

Y4. Techniques of NMR Acoustic Absorption. M. MENES, *University of Pittsburgh*,* AND D. I. BOLEF, *Westinghouse Research Laboratories*.—The technique used in observing nuclear magnetic resonance acoustic absorption is a combination of conventional NMR technique with the composite resonator technique used in ultrasonic measurement. The composite resonator consists of the sample, which has been ground and polished to have flat and parallel faces, to which has been cemented a quartz transducer crystal. This composite resonator is coupled through an impedance matching and inverting network to a Pound-Watkins oscillator. This is followed by conventional synchronous detection equipment. At present the technique has been successful only in materials having small acoustic damping, and for nuclei having fairly strong quadrupole coupling to the lattice. A static quadrupole interaction is, however, not necessary. Under the test conditions, with a sample size of the order of a cubic centimeter, a sensitivity comparable to conventional NMR has been obtained.

* Supported in part by the U. S. Air Force Office of Scientific Research.

Y5. Investigation by Nuclear Magnetic Resonance of the Effects of Pressure on the Thermal Transition and Rotator Phase of 2,2-Dinitropropane.* J. J. BILLINGS AND A. W. NOLLE, *University of Texas*.—The thermal transition for 2,2-dinitropropane, which normally occurs at −5°C, is observed at various pressures up to 1000 kg/cm² in terms of the proton magnetic resonance line width. The spin-lattice relaxation time (T_1) is observed for temperatures from −11°C to 65°C, at atmospheric pressure and under 1000 kg/cm². The compressibility and the specific volume are measured, and x-ray powder patterns are compared, for temperatures above and below the transition. The latent heat of transformation and specific heat, above and below the transition, are calculated. Self-diffusion sets in at the transition, for all pressures studied. Under pressure, molecular rotation in the higher temperature phase, is restricted and T_1 is insensitive to temperature. The correlation time for molecular rotation at atmospheric pressure and 50°C is 7×10^{-12} sec, in fair agreement with dielectric data. The temperature dependence of T_1 suggests that the fraction of molecules subject to rotation in the upper phase increases with the temperature.

* Supported by the Office of Naval Research.

Y6. Hindered Rotation and Nuclear Spin-Spin Interaction. R. STEPHEN BERRY, *Universtiy of Michigan*.—A model of hindered internal rotation is proposed which attributes the main origin of barriers to changes in "long-bond" high-frequency terms in a valence bond expansion of the electronic wave function. On this basis, the ethane barrier of about 3 kcal leads to predicted barriers for methyl silane and methyl germane of 1.65 and 1.5 kcal, respectively. One additional hypothesis, relating the change of spin-pairing to its magnitude, leads to predictions of spin-spin coupling constants between nonbonded hydrogen atoms. The barriers V, the hydrogen-hydrogen exchange integral N_{ss}, and the spin-spin coupling constants $A_{HH'}$ are connected through the approximate relations $A_{HH}\approx329\langle S_H\cdot S_{H'}\rangle$ and $(\langle S_H\cdot S_{H'}\rangle)\approx V[n(3N_{ss}(\text{eclipsed})-2N_{ss}(\textit{gauche})]^{-1}$, where n is the number of near H-H interactions. Predicted values of $A_{HH'}$ are in moderately good agreement with experiment; e.g., 5.7 cps calculated for C_2H_6 *vs* about 7.5 from experiments on similar compounds. Some statements can also be made about the form of the electronic wave function.

Y7. Multiple Quantum Transitions in Nuclear Magnetic Resonance. S. YATSIV, *Stanford University*.—There are many instances in nuclear magnetic resonance experiments where the energy level scheme of the spin system is only slightly different from an equally-spaced Zeeman pattern. In such cases it is possible to induce transitions with $|\Delta m|>1$, in which the simultaneous absorption of several radiation quanta with the same frequency takes place. The theory of these

transitions is developed for the general transitions $\Delta m = n$. In particular, it is found that for rf fields of low amplitudes the n-multiple transition signals grow as the $(2n-1)$th power of the rf amplitudes. This dependence provides a simple way by which the multiplicity of any transition can be determined. Besides being an auxiliary means for analyzing complex magnetic spectra it provides also information on the relaxation processes which is not derivable from ordinary transitions. A method of enhancing multiple quantum transition signals by audio-modulating the radio-frequency is described. This is helpful in cases where the frequency deviations between the various subintervals with $|\Delta m| = 1$ involved in the multiple transition are so large that a direct multiple signal is too weak to be observed. The treatment has been extended to cases where a double quantum transition is induced by a radiation field consisting of two different frequencies. Thus a generalization of the theory of three level masers as well as other cases of double-frequency irradiations, has been obtained.

Y8. Effect of Exchange Interaction on the Energy Levels of Rare Earth Ions in Crystalline Fields. ROBERT L. WHITE, *Hughes Research Laboratories.*—The rare earth elements are characterized by their partially filled $4f$ shells. The electrons occupying this shell combine according to Russell-Saunders coupling to produce states of fixed J, of $(2J+1)$-fold degeneracy in the free ion. When the rare earth ion enters a crystal lattice the crystalline electric fields partially lift the $(2J+1)$-fold degeneracy—giving Stark splittings typically totalling from 100 cm^{-1} to 500 cm^{-1} in magnitude. Optical absorption spectra and low temperature susceptibility measurements have given some information on these splittings, but except for the singular case of Gd (^8S), microwave resonance techniques have not been usable because of the large size of the splittings. In the rare earth garnets, however, exchange energies dependent only on spin coordinates produce additional Zeeman-like displacements of the energy levels of a magnitude roughly equal to the Stark splittings. As a result the energy levels in the presence of a magnetic field are strongly dependent on the crystal orientation relative to the external field, many of the levels crossing as the crystal is rotated. Energy level diagrams for various ions will be presented. It is suggested that microwave paramagnetic resonance investigation of the energy levels near a crossing may be used to study the crystalline fields.

Y9. Effect of Particle Size on Spin-Lattice Relaxation Time.* W. H. TANTTILA AND D. A. JENNINGS, *Michigan State University.*—The spin lattice relaxation time of iodine nuclei in KI has been examined at room temperature and liquid helium temperature. A single crystal and a powder ground from the same single crystal gave the same spin-lattice relaxation time (0.014 sec) at room temperature. However, the spin-lattice relaxation time of the iodine in the single crystal was less (19.2 min) at liquid helium temperature than the relaxation time in the powder (40.4 min). The low-frequency modes are eliminated from the sample by pulverizing it to an extremely fine powder. It is not sufficient to assume that the only lattice modes eliminated are those contributing to the direct-process relaxation. Apparently many of the lattice modes contributing to the indirect process at the helium temperature are also eliminated.

* Work supported by a grant from the National Science Foundation.

Y10. Extension of F. Bloch's Nuclear Induction Boltzmann Equation to Include Exchange Broadening in Liquids. JEROME I. KAPLAN, *U. S. Naval Research Laboratory.*—In a previous paper[1] the author developed a theory for the steady-state NMR spectra of chemically exchanging molecules in liquids. Using a modified approach[2] a set of coupled Boltzmann equations for the mixture of exchanging molecules has been formulated simply by adding additional relaxation terms to Bloch's[3] Boltzmann equations for individual molecules. The general investigation of nonsteady-state phenomena between exchanging molecules is thus possible.

[1] Jerome I. Kaplan, J. Chem Phys. (to be published).
[2] Based on an idea that saw its inception in a conversation with Harden McConnell.
[3] F. Bloch, Phys. Rev. **102**, 104 (1956).

Y11. Observation of Exchange Resonances in Gadolinium Iron Garnet at 24 000 Mc. S. GESCHWIND, L. R. WALKER, AND D. F. LINN, *Bell Telephone Laboratories.*—The internal or exchange field, λM_{Fe}, acting on the Gd in gadolinium iron garnet is known to be relatively low. As a result the zero field resonances at the compensation point ($T_\gamma = 13°C$) given by $\omega \sim \gamma(2H_a\lambda M_{Fe})^{\frac{1}{2}}$ where H_a is the effective anisotropy field, falls in the microwave region. The two modes of resonance corresponding to opposite directions of precession of the sublattices were observed in a small temperature region near the compensation point. A microwave cavity with circular polarization was used to distinguish between these modes. Data were taken at fraction of a degree intervals from 0°C to 25°C right through the compensation point. As a substantial part of the total moment of the sample at compensation in an external field is due to the susceptibility of the Gd, this must be included in the equations of motion. The field for resonance at compensation is roughly given by

$$H \sim \frac{\omega}{\gamma} + \lambda M_{Fe}\left[\omega\left(\frac{1}{\gamma_{Fe}} - \frac{1}{\gamma_{Gd}}\right) + H_A^{Fe} + H_A^{Gd}\right],$$

where H_a^{Fe} and H_a^{Gd} are the anisotropy fields of the Fe and Gd, respectively. Thus the difference in g values between Fe and Gd as well as the anisotropy crucially determine the resonance field.

Y12. Ferromagnetic Resonance Line Widths of Less than One Oersted in Yttrium Iron Garnet. R. C. LECRAW, E. G. SPENCER, AND C. S. PORTER, *Diamond Ordnance Fuze Laboratories.*—A study of ferromagnetic resonance line width in single crystal yttrium iron garnet has been made at 9300 Mc using cavity perturbation techniques. The samples are polished spheres placed at a maximum rf magnetic field in the center of a TE_{10n} transmission cavity, with inside dimensions $0.9 \times 0.93 \times 7.16$ in. A line width ΔH of 2.3 oersteds has been reported previously on this material.[1] In a later batch and with improved polishing techniques, an extremely narrow line width of $\Delta H = 620$ millioersteds has been observed along the hard axis [100]. Line widths along other axes are slightly higher. (ΔH is the *full* width between $\frac{1}{2}\mu_{max}$'' points.) By varying sample diameters, it has been observed in the above cavity that diameters up to approximately 17 mils can be used with no appreciable size effect on the line width, when the samples are properly polished. The diameters used varied from 10 to 17 mils. An important consequence of the 620 millioersted line width is that a spin-lattice relaxation time T of at least 0.18 μsec is indicated at room temperature, using $T \geq 2/(\gamma\Delta H)$. A direct measurement of T by CW methods is described in an accompanying abstract.

[1] LeCraw, Spencer, and Porter, J. Appl. Phys. (to be published).

Y13. Relaxation Phenomena in Yttrium Iron Garnet. E. G. SPENCER AND R. C. LECRAW, *Diamond Ordnance Fuze Laboratories.*—Single crystal yttrium iron garnet (YIG) has been shown to have a ferromagnetic resonance line width of 620 millioersteds (full width) along the hard axis at 9300 mcps. The spin-lattice relaxation time is then at least 0.18 μsec. Because of the appearance of nonlinear effects[1] at microwatts of rf power, methods of measuring the relaxation times at vanishingly small rf power levels have greater accuracy and validity than those using high-power pulse techniques.[2] Also, the method to be described is a CW method

which has other inherent advantages over pulse techniques. A frequency stabilized microwave oscillator is employed together with a variable field permanent magnet and wave guide rather than cavity techniques. A polished YIG sphere is placed in the wave guide in a coil which is 0.1-in. long and 0.05-in. diam and whose axis is in the direction of the dc field. The dc field may thus be modulated to cause a small perturbing modulation of the precession angle of the magnetization. The resulting changes in absorption are observed as changes in the transmitted rf energy. As the modulating frequency is increased the precession angle can not follow because of the relaxation process and the detected ac signal falls off. Relaxation times, measured by this method agree closely with theoretically expected values. Discussion will be given relating these measurements to those obtainable by low-frequency nonresonant methods.

[1] Spencer, LeCraw, and Porter, J. Appl. Phys. (to be published); LeCraw, Spencer, and Porter, J. Appl. Phys. (to be published).
[2] R. T. Farrar, J. Appl. Phys. (to be published).

Y14. Spin-Wave Analysis of Ferromagnetic Resonance in Polycrystalline Ferrites. E. SCHLÖMANN, *Raytheon Manufacturing Company.*—A theory of ferromagnetic resonance is developed in which dipolar interaction is taken into account by means of the spin-wave formalism in a manner described by Geschwind and Clogston.[1] Owing to crystalline anisotropy and the polycrystalline character of the material, the homogeneous mode of precession interacts with spin waves whose wavelength is of the order of or larger than the average linear grain size. The moments of the absorption line are calculated for the case of vanishingly small single crystal line widths. Line width and line shift owing to crystalline anisotropy are calculated by a perturbation-like approach in which interactions which do not involve the homogeneous mode are neglected. The theory predicts a very strong frequency and shape dependence of the line width for the case in which the homogeneous mode is approximately degenerate with long wavelength spin waves propagating in directions perpendicular to the dc field. At high frequencies the anisotropy contribution to the line width should approximately equal $2H_a^2/4\pi M$ (H_a=anisotropy field). For spherical samples it should reach a maximum at the frequency $2/3\gamma 4\pi M$ and should be very small at lower frequencies.

[1] S. Geschwind and A. M. Clogston, Phys. Rev. 108, 49 (1957).

SATURDAY AFTERNOON AT 2:00

Eckhart 133

(CONYERS HERRING presiding)

Mostly Solid-State Theory

Z1. Energy Band Interpolation Scheme Based on a Pseudopotential. JAMES C. PHILLIPS, *Bell Telephone Laboratories.*—Most energy band calculations have been limited to symmetry points of the Brillouin zone, because of the simplifications in the secular equation resulting from high symmetry. Often, however, one would like to obtain energy values elsewhere in the zone. For this reason Slater and Koster[1] proposed an interpolation scheme based on the tight-binding (LCAO) approximation. A different scheme is presented here, based on the orthogonalized plane wave viewpoint. A pseudopotential is introduced, which greatly reduces the number of parameters, and makes it possible to include the effects of configuration interaction correctly. Arguments will be presented which suggest that the approach should represent a good physical approximation for metals and semiconductors. Results for the energy bands of silicon will be discussed.

[1] J. C. Slater and G. F. Koster, Phys. Rev. 94, 1498 (1954).

Z2. Many-Electron Wave Function. L. ONSAGER, *Yale University.*—Gell-Mann and Brueckner[1] showed that in computing the "first-order" correlation energy for a system of electrons, the exchange effects may be superimposed as an afterthought. Accordingly, we consider the eigenwert problem in which the interaction potential consists of a single Fourier component. A slight elaboration of Sawada's commutation rules[2] completes the appropriate Lie algebra. The exact solution of the simplified eigenwert problem is reduced thus to a Wiener-Hopf equation which has the propagator of Gell-Mann and Brueckner for its kernel. Previous results for the energy[1,2] are confirmed.

[1] M. Gell-Mann and R. A. Brueckner, Phys. Rev. 106, 364 (1957).
[2] K. Sawada, Phys. Rev. 106, 372 (1957).

Z3. Phases of Bloch Functions and the Localization of Wannier Functions.* JOHN B. GIBSON, *Brookhaven National Laboratory.*—A Bloch function $b(\mathbf{r},\mathbf{k})$ may be obtained by analytic continuation from some nondegenerate point in $\mathbf{k}$ space by the "$\mathbf{k}\cdot\mathbf{p}$ method." A periodic array of branch surfaces may be necessary so that the path of analytic continuation does not thread closed curves of degenerate points producing a multiple valued $b(\mathbf{r},\mathbf{k})$. Thus $b(\mathbf{r},\mathbf{k})$ will have a phase change across these branch surfaces. In addition $b(\mathbf{r},\mathbf{k})$ will not in general be periodic in $\mathbf{k}$ space but will shift in phase going from one BZ to the next. The choice of a phase function that will eliminate these phase shifts and give a Bloch function periodic in $\mathbf{k}$-space and having no discontinuities except in the neighborhood of degenerate points will be discussed. It can be shown that this choice of phase will produce the most localized Wannier function. This is desirable so that the method of effective mass[1] be applicable to the largest class of perturbing potentials. The gradient of this phase function also enters in the "crystal momentum" representation of Adams.[2]

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] J. C. Slater, Phys. Rev. 76, 1592 (1949).
[2] E. N. Adams II, J. Chem. Phys. 21, 2013 (1953).

Z4. Self-Consistency in Band Calculations.* M. L. GLASSER AND J. CALLAWAY, *University of Miami.*—It has been a usual procedure in band calculations to include the effects of the valence electron distribution by assuming it to consist of overlapping spheres of uniform charge density. This is not self-consistent and we have developed a procedure within the scope of the OPW method, for taking the symmetry and radial dependence of the distribution into account. A valence charge distribution in the unit cell is obtained from an initial estimate of the electron wave functions and Poisson's equation is used to obtain the Fourier coefficients of the desired potential. As a test, the procedure has been applied to silicon and

the results compared with those obtained from a spherical approximation.

* Supported by the Office of Naval Research and the Air Force Office of Scientific Research.

Z5. Partially Correlated Systems of Electrons. HAROLD SALWEN, *Harvard University.*—We consider a division of the electrons in a many electron system into k groups of correlated electrons, with no correlation between groups being considered. The wavefunction then takes the form $\Psi = C\Sigma_{(P)} \pm P\varphi_1(\mathbf{r}_{11},\cdots,\mathbf{r}_{1n_1}) \times \varphi_2(\mathbf{r}_{21},\cdots,\mathbf{r}_{2n_2})\cdots\varphi_k(\mathbf{r}_{k1},\cdots,\mathbf{r}_{kn_k})$ with φ_i an antisymmetric function of its n_i coordinates. It is most convenient to require an orthogonality relation,

$$\int \varphi_i^*(\mathbf{r},\mathbf{r}_{i_2},\cdots,\mathbf{r}_{in_i})\varphi_j(\mathbf{r},\mathbf{r}_{j_2},\cdots,\mathbf{r}_{jn_j})d\tau = 0$$

for $i \neq j$, as well. We derive the equations to be satisfied by the φ_i, in order that Ψ approximate an eigenfunction of the Hamiltonian, and discuss some applications. In a metal, correlation among conduction electrons *or* between a conduction electron and the nearest ion core can be treated by this method but not both simultaneously. Application to a metallic crystal indicates the extent to which the quantum defect method takes account of correlation between valence and core electrons.[1,2]

[1] F. S. Ham, *Solid State Physics*, F. Seitz and D. Turnbull, editors (Academic Press, Inc., New York), Vol. 1, p. 127, esp. pp. 169 ff.
[2] H. Brooks and F. S. Ham (to be published).

Z6. Ground-State Energy and Effective Mass of the Polaron in a Periodic Potential. E. LIEB AND J. YAMASHITA, *University of Illinois.*—In the usual treatment of the polaron in a periodic potential the effective mass equation is usually used; that is to say one replaces the exact Hamiltonian by a polaron Hamiltonian in which the electron mass is replaced by the band effective mass. This method is without justification and may be shown to be incorrect in some cases, particularly when the polaron coupling constant, α, or the periodic potential $V(r)$ become large. We wish to propose a method which, from numerical comparison with easily calculable cases, we believe will yield at least approximately correct results for the ground-state energy and effective mass for all values of α and $V(r)$. The method uses not only the effective mass of the electron in the periodic potential but requires in addition knowledge of the dependence of this quantity on the electronic mass.

Z7. Influence of Lattice Distortion on Scattering by Point Defects. W. A. HARRISON, *General Electric Research Laboratory.*—The cellular method for constructing wave functions in distorted lattices, which has been previously described by the author, is used to study the influence of lattice distortion on the scattering by point defects in monovalent metals. A point defect may give rise to a local dilatation, to shear strains which fall off as $1/r^3$, and to an additional uniform lattice dilatation. The local dilatation modifies the effective charge and the effective radius of the center and may cause important changes in the scattering. The shear strains may also modify the effective charge and radius, but the effect is small in most monovalent metals due to the weakness of the coupling between electrons and shear strains. The effect of the additional uniform dilation is generally negligible.

Z8. Nuclear Quadrupole Coupling in Polar Molecules. G. BURNS, *IBM Research Center, Poughkeepsie.*—The antishielding factor, $(1-\gamma_\infty)$,[1] is calculated for a point charge outside a spherical ion. It can be shown that $(1-\gamma_\infty)$ is the same for any axially symmetric charge distribution outside the ion. In particular, one can consider in an alkali halide gas, the contribution to $\partial^2 V/\partial Z^2$, (q), at the alkali nucleus due to (1) a charge, (2) an induced dipole moment, and (3) an induced quadrupole moment at the halide position. The moments are induced by the alkali ion. The contributions to q from the previously neglected terms 2 and 3 are almost as large as 1. The octupole and hexadecapole polarizabilities for Cl^- have been calculated and the quadrupole polarizability[2] has been re-examined. The sum of the terms appears to converge but the effects are large. These corrections applied to the alkali ions decrease the experimental $(1-\gamma_\infty)$.[3] Thus the agreement between theory and experiment is poorer except in the case of Na^+.

[1] Foley, Sternheimer, and Tycko, Phys. Rev. **93**, 734 (1954).
[2] R. M. Sternheimer, Phys. Rev. **107**, 1565 (1957). Dr. Sternheimer kindly supplied the perturbed wave function necessary to calculate α_Q.
[3] The experimental $(1-\gamma_\infty)$ is defined by the measured quadrupole coupling divided by eQq/h, where q contains no shielding effects.

Z9. Entropy as a Measure of Diversity. JEROME ROTHSTEIN, *Edgerton, Germeshausen & Grier, Inc.*—It is shown that qualitative intuitive notions of diversity and similarity for a collection of objects can be made precise and quantitative. The discussion leads to a new interpretation of entropy as a measure of diversity, with reduction in entropy characteristic of what may be called unification. Any equivalence relation in a set partitions the set into mutually exclusive subsets of zero diversity with respect to the categorical scheme induced by the equivalence relation. Uses of entropy as measures of information or organization have been shown to apply to scientific theory, leading respectively to describing the function of theory as minimizing the information contained in experimental data (predictable data convey no information), or organizing observation.[1] *A quantitative measure of the unifying of theory is given by means of this new interpretation of entropy.* Entropy and measurement in quantum mechanics appear in a new light; an eigenstate of an operator is one of zero diversity for that operator, but not for a noncommuting operator—*an entropy or diversity metric for operator space* is suggested.

[1] Rothstein, Rev. internationale de philosophie, No. 40 (1957), Fasc. 2, and *Communication, Organization and Science* (Falcon's Wing Press, Indian Hills, Colorado).

Author Index to Papers Presented at the Chicago Meeting

Addiss, R. R., Jr.—Q10
Ager, R.—UA2
Akamatu, H.—UA9, UA10
Alder, Bernard—VA1
Alers, G. A.—M10
Alger, R. S.—UA13
Allgaier, R. S.—LA12
Anderson, John H.—UA5
Anderson, T. H.—UA13
Andrew, J. F.—UA10
Andrews, R. D.—G7
Anseli, G. S.—JA7, JA8
Anthony, R. L.—T5
Arrott, A.—BA2
Attard, A. E.—LA5
Azaroff, L. V.—GA8
Azuma, T.—D5
Bacon, R.—FA14
Baker, G. S.—FA6
Baker, John A.—UA8
Ballam, J. A.—D8
Balluffi, R. W.—Q5
Bate, R. T.—LA2
Bath, H. M.—V8
Batterman, Boris W.—FA3
Bear, R. S.—B2
Becker, J. H.—J5
Beer, A. C.—C2, FA5, LA2
Bemski, G.—UA3
Berry, R. Stephen—Y6
Bessey, W. H.—QA5
Billings, J. J.—G6, Y5
Birman, J. L.—LA13
Blakemore, J. S.—C3
Bloembergen, N.—N1, S1
Blunt, R. F.—J8
Bolef, D. I.—Y3, Y4
Bollinger, L. M.—D3
Bowers, R.—LA4
Boyd, D. R.—V5
Boyd, R. H.—SA5
Boyle, W. S.—TA10
Bragg, R. H.—GA8, JA1
Bramley, A.—J11
Bray, Ralph—J7
Brayton, D. E.—J2
Brebrick, R. F.—J2
Brennan, W. D.—V4
Brewer, D. F.—TA1
Broadhurst, Martin G.—G2
Brophy, James J.—H6
Broudy, R. M.—E6, FA4
Brown, Frederick C.—QA11, QA12
Brown, H.—QA5
Brueckner, Keith—VA3
Bruner, L. J.—M6
Bube, Richard H.—J12, J13
Burns, G.—Z8
Burstein, E.—QA3, R8
Buttrey, John W.—BA3
Callaway, J.—Z4
Campos, F. P.—GA9
Cartwright, D. R.—D5
Chaberski, A.—BA6
Choyke, W. J.—V1
Chynoweth, A. G.—H1
Claxton, W. E.—T2
Cleland, J. W.—XA8
Cleveland, Forrest F.—W7, W8
Coleman, Bernard D.—T8
Coleman, R. V.—FA13
Collier, R. S.—FA2
Compton, W. Dale—A2
Conwell, E. M.—C6
Crawford, J. H., Jr.—UA6, XA8
Crittenden, R. R.—D8
Crystal, Eugene—SA8
Cunningham, R. W.—J7
Cutler, M.—V8
Cuykendall, T. R.—M7
Daniels, W. B.—M8
Dannis, M. L.—T1
Darby, J. B., Jr.—Q5
Dash, W. C.—FA1
Dauenbaugh, C. E.—V6
Daunt, J. G.—TA1
Decker, D. L.—TA4, TA5
Deeley, C. W.—G4
De Maria, G.—W9
Dewald, J. F.—R10
deWit, G.—M2
Dienes, G. J.—JA10
Dixon, Jack R.—LA6
Dowling, Jerome M.—W6
Drabble, J. R.—LA11
Dreyfus, R. W.—BA14, JA4
Drowart, J.—W9
Duga, J. J.—FA5
Enns, J. H.—BA10
Erlbach, E.—TA3
Etzel, Howard W.—QA7
Ewald, A. W.—R1
Ewing, R. D.—UA12
Fan, H. Y.—C4, LA10, R5, R7
Feher, G.—UA3
Ferry, John D.—G1
Fisher, P.—R5
Fitzgerald, Edwin R.—G2, G3
Freeman, A. J.—GA11
Friauf, R. J.—QA12
Fuschillo, N.—SA7, SA9
Gärtner, W. W.—C5
Garwin, R. L.—TA2, TA3
Gere, E.—UA3
Geschwind, S.—Y11
Gibbs, P.—FA2, FA6
Gibson, John B.—Z3
Gilman, J. J.—FA7, FA8, FA9, U4
Glasser, M. L.—Z4
Glenn, D. C.—D6
Glicksman, M.—LA8
Gold, Raymond—W6
Goldburg, W. I.—XA10
Goldstein, S.—C5
Gordon, D. I.—JA9
Gordon, Robert B.—A3
Gourary, Barry S.—A1
Granato, A. V.—FA12
Greene, L. C.—FA15
Groves, R. D.—LA11
Gubner, E.—J2
Hall, C. E.—B1
Hall, T. C.—V9
Harkness, A. L.—D2
Harrison, W. A.—Z7
Heaton, LeRoy—GA9
Heikes, R. R.—BA1
Henderson, D. J.—D2
Henvis, B. W.—R8
Hewitt, F. G.—T5
Hill, D. E.—XA5
Hill, J. E.—H7
Hoare, F. E.—Q7
Hoffman, Dorothy M.—GA5
Holland, R. E.—D4
Holmes, D. K.—FA11
Hook, H. O.—BA12
Hopfield, J. J.—QA1, QA2
Huang, Kerson—VA4
Hudson, R. P.—X1
Hughes, D. J.—GA12
Huizenga, J. R.—D2
Huntington, H. B.—P2
Ingham, H. S., Jr.—XA13
Inghram, M. G.—W9
Ivey, D. G.—T3
Jacobsen, E. H.—P3
Jamison, R. E.—JA13
Jeffries, C. D.—F2
Jennings, D. A.—Y9
Johnson, C. Curtis—J6
Johnston, W. D.—BA1
Johnston, W. G.—FA7, FA8, FA9
Känzig, Werner—A4
Kaplan, Jerome I.—Y10
Karplus, Dean—L2
Katz, E.—BA10
Kernohan, R. H.—JA11, JA12
Khoury, F.—SA4
Kies, J. A.—M1
Kikuchi, C.—UA2
Kikuchi, R.—BA2
Kimura, H.—M3, Q9
Klontz, E. E.—XA3
Kobayashi, Koichi—XA10
Koehler, J. S.—M2, U3
Koenig, Seymour H.—H4, H5
Kokoszka, F. T.—D5
Kortright, J.—XA4
Kramers, H. C.—TA1
Krautkopf, D. W.—SA9
Krimm, S.—G10
Kroener, C.—BA9
Krumhansl, J. A.—P4
Kuhlmann-Wilsdorf, D.—M3, Q9
Kurath, F.—G1
Kurbatov, J. D.—D5, D6
Laff, R. A.—C4
Lambe, John—UA8
Lampert, M. A.—J3, J4
Lark-Horovitz, K.—C1, XA3, XA5
Lawson, Andrew W.—QA13
Lax, Benjamin—R2, R3
Lax, Melvin—E2
Learn, A.—GA3
LeCraw, R. C.—Y12, Y13
LeGrand, Donald—SA2
Leivo, William J.—J6
Levy, Paul W.—BA14, JA3, JA4
Li, James C. M.—Q11
Liang, C. Y.—G10
Lichtenstein, R. M.—Y2
Lieb, E.—Z6
Lind, Edward L.—J12, J13

Linn, D. F.—Y11
Loebner, E. E.—BA12
Loferski, J. J.—XA1, XA2
Longo, T. A.—C1, XA7
Ludwig, G. W.—UA4
Lummis, Frances L.—J2
Luyet, B.—BA9
Lynch, F. J.—D4
Lyons, W. James—SA3
Machlup, S.—R11
MacKay, J. W.—XA3, XA4
Maddin, R.—M3, Q9
Mallard, W. C.—Q1
Mandel, Elaine R.—SA6
Manning, J. R.—Q6
Mapes, J. E.—JA4
Mapother, D. E.—TA4, TA5
Maringer, R. E.—FA5
Marion, J. P.—D3
Mark, H. F.—K1
Marshall, S. A.—UA11
Matarrese, L. M.—UA2
Matthias, B. T.—TA7
McClure, J. W.—E5
McConnell, H. M.—L3
McCrum, N. G.—K3
McIntosh, H. H.—FA2
McLean, A. D.—W3
Meister, Arnold G.—W6, W7
Menes, M.—Y3, Y4
Mergerian, D.—BA11
Merryman, P. I.—W3
Mette, H.—C5
Meyer, Horst—X2
Millea, M. F.—C9, V9
Miller, Robert C.—BA4
Miller, S. I.—W8
Miller, W.—QA5
Montroll, E. W.—VA2
Morgan, Henry M.—T6
Mori, Hazime—E3
Moss, M.—QA8, QA9
Moszkowski, Steven A.—D9
Motz, J. W.—D7
Mrozowski, S.—BA5, BA6, UA9, UA10
Muldawer, Leonard—GA5
Mulliken, R. S.—W2
Nash, H. C.—M9
Neighbours, J. R.—M10
Nelson, C. M.—UA6
Nelson, J. R.—QA2
Nicholls, R. W.—BA8
Ninomiya, Kazuhiko—G9
Nolle, A. W.—G6, Y5
Nowick, A. S.—M5, U1
Ohlsen, P.—QA5
Onsager, L.—Z2
O'Reilly, D. E.—Y1
Palmer, D. R.—V6
Pare, V. K.—M7
Parkinson, W. H.—BA8
Parlett, H. W.—D6
Paskin, A.—GA7
Patrick, Lyle—V1
Pearson, G. L.—H1, V7
Pell, E. M.—R6
Petrauskas, A. A.—T7
Petritz, Richard L.—J1, J2
Phillips, James C.—Z1
Phillipson, E.—W2
Picus, G. S.—QA3, R8
Piotrowski, E. A.—W8
Placious, R. C.—D7
Pohl, Robert G.—LA3
Porter, C. S.—Y12
Porter, Lew F.—JA10
Powell, R. S.—Y2
Prager, Stephen—Q3
Rabin, Herbert—QA6
Rado, George T.—F1
Ramdas, A. K.—LA10, R7
Ramler, W. J.—D2
Raney, J. K.—JA5
Ransil, B. J.—W3
Rapatz, G.—BA9
Rappaport, P.—XA1, XA2
Ray, R. K.—C1
Reich, H. A.—TA2
Reid, F. J.—C2
Reiffel, L.—V2
Reiss, Howard—Q4
Reneker, Darrell H.—M4
Reynolds, D. C.—FA15
Rich, A.—B3
Richardson, J. W.—W3
Riseman, Jacob—GA5
Roberts, C. C.—JA2
Robinson, R. J.—J9, J10
Roothaan, C. C. J.—W1, W3
Rose, A.—J3, J4
Rosenstock, Herbert B.—GA1
Roth, Laura M.—R2, R3
Rothstein, Jerome—Z9
Rudd, J. F.—G7
Ruedenberg, K.—W3
Sack, H. S.—M7, Q10
Salkovitz, E. I.—JA7, JA8
Salwen, Harold—Z5
Sandler, Y. L.—TA9
Sarachik, M.—TA3
Sato, H.—BA2, M10
Sauer, J. A.—G4, SA7, SA9
Scandrett, J. H.—D8
Schillinger, W.—H5
Schindler, A. I.—JA7, JA8
Schlömann, E.—Y14
Schnepp, O.—BA13
Schumacher, R. T.—XA10
Scott, R. E.—GA6
Sears, G. W.—FA9
Seeger, Karlheinz—H3
Seraphim, D. P.—M5
Sery, R. S.—JA9
Shaw, R. W.—TA4, TA5
Shephard, W. D.—D8
Shucker, H.—V4
Sidhu, S. S.—GA9
Siegel, I.—UA11
Siegert, A. J. F.—W4
Sihvonen, Y. T.—V5
Silsbee, H. B.—X4
Sinnott, K. M.—G5
Sivertsen, John—Q8
Slichter, W. P.—SA6
Slifkin, L.—Q1, Q2
Slutsky, L. J.—GA4
Smith, Charles S.—M8, M9
Smith, Cyril Stanley—BA7
Smith, George E.—QA13
Smith, H. L.—M1
Smith, Roland W.—R9
Smoluchowski, R.—JA2, XA11, XA12, XA13
Sochard, I. I.—J5
Soule, D. E.—E7
Spear, W. E.—XA3
Spence, R. D.—UA12
Spencer, E. G.—Y12, Y13
Spiewak, M.—TA6
Spilners, Aija—JA2
Sproull, R. L.—QA8, QA9
Squire, C. F.—TA8
Sreedhar, A. K.—TA1
Statz, Hermann—V11
Steele, M. C.—H2
Stein, Richard S.—SA2
Stern, Frank—LA7
Stevens, J. R.—T3
Straube, B. W.—SA1
Strauss, Alan J.—LA1, LA5
Suhl, H.—F3
Sundaram, S.—W8
Tanttila, W. H.—Y9
Tauber, G. E.—E1
Taylor, J. H.—LA9
Teegarden, K. J.—QA10
Teng, L. C.—D1
Teramoto, Ei—W4
Thompson, D. O.—FA11
Thorsen, A.—TA8
Tomizuka, C. T.—Q5
Tompkins, E. H.—J9
Townes, Charles H.—F4
Townley, C. W.—D6
Treaftis, H. N.—JA14
Treuting, R. G.—V7
Tsukada, Kineo—D4
Tucker, C. W., Jr.—JA14
Tucker, R. N.—FA6
Tufte, O. N.—R1
Tweet, A. G.—C7
Tyler, W. W.—C7, R4
Valenta, M. W.—C8
Vanas, D. W.—SA1
VanHeyningen, Roger—QA11
Van Ostenburg, D. O.—UA11
van Vliet, K. M.—H7
Venables, J. D.—FA4
Vineyard, George H.—GA10, K4
Virgin, H. S.—SA8
Wakelin, J. H.—SA8
Walker, L. R.—Y11
Walker, R. M.—U2
Walker, W. D.—D8
Wall, R. A.—SA7
Wallis, Richard F.—GA2
Wang, E. Y.—XA7
Wanlass, F. M.—FA6
Warren, B. E.—P1
Watkins, G. D.—UA1
Watson, M. D.—BA8
Watts, H. V.—V3
Webb, L. A.—UA13
Wechsler, M. S.—JA11, JA12
Weeks, Robert A.—UA7
Weeks, R. F.—QA10
Weertman, J.—K2
Weigman, B. J.—T7
Weil, John A.—UA5

Weinrich, G.—C11
Weinstock, H.—QA8, QA9
Weisbrod, H.—QA5
Weiser, Kurt—C10
Weiss, A.—W3
Weissman, Herman B.—W7
Weissman, S.—L1
Wert, Charles—Q8
Wertheim, G. K.—XA6
Wheatley, J. C.—X3
White, Robert L.—Y8
Whitsett, Charles R.—XA9
Widom, B.—W5
Wiegand, D. A.—XA11, XA12
Willardson, R. K.—C2, LA2
Williams, G. P.—Q2
Williams, M. L.—G8
Wing, J.—D2
Wobschall, D.—UA9
Wolfe, R.—LA11
Wood, Lawrence A.—T4
Woodbury, H. H.—UA4
Woodward, A. E.—SA7, G4
Yamashita, J.—QA4, Z6
Yatsiv, S.—Y7
Yin, Theodore P.—G1
Yoshimine, M.—W3
Young, F. W., Jr.—FA10
Zauberis, D. D.—GA9
Zemel, Jay N.—E4
Zimm, B. H.—T9
Zimmerman, J. E.—Q7
Zitter, R. N.—LA5
Zwerdling, Solomon—R2, R3

Reminder of the 1958 Washington Meeting

As stated in the January issue of this Bulletin, hotel reservations are to be made by writing to the Sheraton-Park Hotel, Washington 8, D. C., and specifying that the writer is coming to this meeting. The Sheraton-Park engages to provide rooms in other hotels after its own are fully booked; our members may designate the hotels of their second choice. The dates of the meeting are May 1–3, and the deadline-date is Friday, February 21.

Preliminary Announcement of the 1958 Ithaca Meeting

The 1958 Summer Meeting in the East will be held at Ithaca, New York, in the buildings of Cornell University, on June 19, 20, and 21. Information about hotels and motels is promised for the Washington Bulletin. Deadline is Friday, April 18.

Officers of Divisions Convening at This Meeting

Division of High-Polymer Physics. Chairman, A. M. Bueche; *Vice-Chairman*, Robert Simha; *Secretary-Treasurer*, W. James Lyons (office at Textile Research Institute, Princeton, New Jersey).

Division of Solid-State Physics. Chairman, S. L. Quimby; *Vice-Chairman*, J. C. Slater; *Secretary-Treasurer*, E. Burnstein (office at U. S. Naval Research Laboratory, Washington 25, D. C.); *other members of Executive Committee*, L. Apker, N. Bloembergen, J. G. Daunt, W. Kohn, W. T. Read, C. G. Shull, C. Zener.

Division of Chemical Physics. Chairman, D. F. Hornig; *Vice-Chairman*, Elliott Montroll; *Secretary*, J. R. Platt; *Treasurer*, F. G. Brickwedde; *other members of Executive Committee*, G. Herzberg, B. L. Crawford, C. A. Hutchison, R. S. Halford. *Incoming Secretary-Treasurer:* A. A. Frost, Northwestern University, Evanston, Illinois.

To join any of these Divisions, send a check for $2.00 to its Secretary-Treasurer; make out the check to the Division in question. This privilege is reserved to members of the Society.

MEETINGS AND DEADLINES FOR 1958

Place	*Meeting dates*	*Deadline date*
Chicago	March 27–29	past
Washington	May 1–3	February 21
Ithaca, New York	June 19–21	April 18
Vancouver, *British Columbia	August 26–28	June 27
Chicago	November 28–29	September 26
Los Angeles*	December 18–20	October 17

* Abstracts for the Vancouver and Los Angeles meetings are to be sent to W. A. NIERENBERG, University of California, Berkeley 4, California, and must reach his office not later than the corresponding deadline date.

Abstracts for the other meetings listed above are to be sent to KARL K. DARROW, American Physical Society, Columbia University, New York 27, New York, and must reach his office not later than the corresponding deadline date. Take note that abstracts mailed the day before deadline-day often fail to arrive in time: the last postal delivery of the day usually comes to our office before 2 P.M. Allow at least two days for abstracts sent by airmail from points east of the Mississippi, and longer for those sent from farther west. To avoid chance of confusion, please do not send an abstract for any meeting until the deadline date of the previous meeting is at least five days past. *The privilege of contributing papers to meetings of the American Physical Society is restricted to the members of the Society and to nonmembers whose papers are sponsored by members.*

RULES AND INSTRUCTIONS FOR THE PREPARATION OF ABSTRACTS

The Council has ordered that abstracts shall be not longer than two hundred (200) words or the equivalent thereof. In reckoning equivalence, a footnote is equated to ten words; each line in a table to ten words; a "display" formula—one that requires a line to itself—is an expensive luxury equated to forty words.

Two copies of each abstract must be sent to the appropriate office. They must be typewritten; one must be an original, the other may be an original or a carbon copy. *They must be double-spaced:* single-spaced manuscripts are too crowded to permit the editorial markings to be made with ease and clearness. Each abstract must be confined to a single page: if it is too long for a single page it is too long to be printed. *If we receive an abstract typed on two pages, we print only its first page.* Write each abstract as a single paragraph: the suppression of paragraphs costs time and labor to the editors. Do not use very thin paper; a sheet of very thin paper may cause extraordinary trouble when mixed with sheets of reasonable thickness. Look at the abstracts in this *Bulletin* to see how the title of the paper and the name of the author are to be arranged, and follow the example. Issues of the *Bulletin* are always appreciably delayed because the editors have to do what the authors should have done.

Remember the rule of the Council that, if an author submits more than one abstract, all but one must go onto the Supplementary Programme. In enforcing this rule, an abstract is credited to the author whose name appears first in the by-line.

It now becomes an expensive business to make any change in an abstract, even the smallest, after the abstract has gone to press. By order of our Council "A change in an abstract will be permitted only at the discretion of the Secretary or his deputy, and only if TEN DOLLARS is enclosed with the letter in which the change is requested." As heretofore, an abstract will not be withdrawn from proof unless the asker sends ten dollars with his request.

Important Notice about the New Membership List

A new Membership List of the American Physical Society will be issued during 1958. Return-addressed postal cards have already been mailed to all Members and Fellows of the Society, except those who were elected in November, 1957. If you were already a member in November, 1957, but have not received such a card, write *at once* for a card to Professor Shirley L. Quimby, Pupin Physics Laboratories, Columbia University, New York 27, New York. If you were elected in November, 1957, and have since changed your address, do likewise. Candidates who are elected in January, 1958, *and who accept election* will be entered in the List with the addresses that they submit in their acceptance.

Proceedings of the American Physical Society

Minutes of the Fall Meeting of the New England Section at Bowdoin College, Brunswick, Maine on October 19, 1957

THE New England Section of the American Physical Society held its annual Fall Meeting on Saturday, October 19, at Bowdoin College, Brunswick, Maine. There was a total registration of 65 persons. At the morning session six stimulating research papers were given.

After a luncheon as the guests of the college, the following council members were elected to serve until the next Fall Meeting:

Chairman	R. P. Winch (Williams)
Vice Chairman	M. A. Jeppesen (Bowdoin)
Secretary-Treasurer	R. F. Kingsbury (Trinity)
Executive Committee	H. H. Hall (New Hampshire)
	P. J. Bray (Brown)

Following the business meeting four invited papers were given.

Physical Aspects of Biological Synthetic Mechanisms. Ernest C. Pollard, *Yale University.*

Recent Advances in Polarized Light and Its Application. William A. Shurcliff, *Polaroid Corporation.*

Semiconductors at High Pressures. William Paul, *Harvard University.*

A Ferromagnetic Microwave Amplifier. Lester Hogan, *Harvard University.*

Robert F. Kingsbury, *Secretary-Treasurer*
New England Section

Contributed Papers

1. Detuned Multilayer Films for Mirrors and Filters.* M. A. Jeppesen, *Bowdoin College.*—Measurements of the reflectance of aluminized mirrors coated with dielectric multilayers are compared with the theoretical reflectance calculated with the aid of a card programed electronic computer. Attention is given to the use of detuned[1,2] dielectric multilayers to increase the band width over which the reflectance is high. Detuning causes a narrow low-reflectance band to appear which interrupts an otherwise broad-band high-reflectance region. The cause of the low reflectance is related to the rapid variation with wavelength of the phase shift on reflection in the film. Attempts to eliminate it have failed. Previously reported results[3] on filters made with detuned multilayers are extended. These filters are characterized by three or four narrow pass bands. The dependence of pass frequencies on spacer thickness is much less for the conventional tuned film filter. Computed and observed characteristics of several thirty-one layer filters are given. A transmission band width of twelve angstroms is obtained experimentally as compared with a calculated value of six angstroms. The agreement is reasonable considering the difficulty of accurate control over the individual layer thicknesses and the assumptions made in the calculations.

* Supported by the National Science Foundation.
[1] S. Penselin and A. Steudel, Z. Physik **142**, 21 (1955).
[2] P. W. Baumeister and J. M. Stoue, J. Opt. Soc. Am. **46**, 228 (1956).
[3] P. W. Baumeister and F. A. Jenkins, J. Opt. Soc. Am. **47**, 57 (1957).

2. Ion Beam Formation and Optics in the Tandem Electrostatic Generator. R. J. Connor, J. L. Danforth, A. J. Gale, and P. H. Rose, *High Voltage Engineering Corporation.*—A 10-Mev Van de Graff electrostatic generator is described which makes use of charge exchange to double its effective voltage. Negative hydrogen ions are injected into the accelerator at an energy of 80 kev and accelerated to the terminal (potential V) where the electrons attached to each ion are stripped leaving a beam of protons with an energy of $V+80$ kev. The beam of protons obtained in this way is then accelerated to ground potential and has a final energy of $2V+0.08$ Mev. Ions of any element that can form negative ions can be accelerated in this way. Advantages of this type of accelerator, often known as a tandem accelerator, will be discussed. The negative ion source and the ion optics will be described, together with the physical measurements which were made to assist in the design of the accelerator.

3. Idea of a Particle in Physics. David Park, *Williams College.*—Any conceptual model which is made in order to clarify the results of experiments and theories in microphysics must justify itself by introducing less confusion than it removes. The particle is a model, plausible because it provides an easy visualization of the mechanisms behind certain microscopic phenomena in terms of common experience. These advantages are more than offset, in the writer's opinion, by the fact that such things as the superposition of wave functions become incomprehensible unless one transcends the model completely. Further, the intuitive idea of a particle leads to irrelevent hypotheses and questions. The following alternative language has been proposed.[1] A piece of apparatus defines a set of orthogonal states in space-time and a measurement amounts to a determination of the occupation numbers of some of these states. The terminology of second quantization (though not its mathematics) is thus introduced from the beginning and attention is on the apparatus and its response rather than on the "particle." Further, it is now possible to discuss the complementarity theory and the correspondence principle in very simple and general terms.

[1] O. Costa de Beauregard, Rev. gen. sci. pure et appl. et Bull. assoc. franç. avance. sci. **62**, 165 (1955).

4. Diffraction Theory of Aberrations.* George C. Krueger, *University of Maine.*—A survey of the work on the diffraction theory of image formation will be given. Rayleigh's

and Abbe's investigations, involving essentially the same limitations as Kirchhoff's formulation of Huyghens' principle, provided the first satisfactory explanation of image formation. In 1934, Zernike proposed an alternative series development for the aberration function in a series of orthogonal polynomials.[1] Each term in this expansion characterizes a single aberration. Theoretical and experimental work by Zernike's students,[2] based on his ideas, has provided a satisfactory explanation of image formation in the presence of small amounts of aberrations. Marechal has investigated both theoretically and experimentally the contrast in optical images and the loss of contrast in the presence of moderate amounts of aberrations.[3] N. van Kampen developed an asymptotic expansion of the diffraction integral for short wavelengths.[4] These papers help one to gain a clear understanding of the phenomenon. Diffraction patterns formed in planes other than the Gaussian image plane have been used in this laboratory to investigate in detail the way in which aberrations and scattered light modify an image.

* Work supported by the National Science Foundation and The University of Maine Coe Research Fund.
[1] F. Zernike, Physica 1, 689 (1934).
[2] B. R. A. Nijboer, Physica 10, 679 (1943); 13, 605 (1947); K. Nienhuis and B. R. A. Nijboer, Physica 14, 590 (1949).
[3] A. Marechal, "Optical image evaluation," B.B.S. Cir. 526, Paper 2.
[4] N. G. van Kampen, Physica 14, 575 (1949); 16, 817 (1950).

5. Nuclear Magnetic Resonance Studies of Radiation Damage.* P. J. Bray, *Brown University.*—Nuclear magnetic resonance (NMR) techniques are being used to detect and study radiation damage in solids. Investigations of alkali halide single crystals which have received reactor irradiation have yielded measurements of the number of defects formed and their manner of distribution in the crystals. The work indicates that even defect densities of less than one defect per hundred thousand atoms can be studied with NMR techniques in some materials. Radiation damage effects are also under study in molecular solids which have received gamma irradiation. The resonance intensity changes can be used to determine the amount of bond breakage in the solid. All of the present studies depend upon an understanding of the nuclear electrical quadrupole moment and its coupling to the electric field gradient at the site of the nucleus.[1] A brief discussion will be given of these and other topics, including the basic theory[2] of NMR and the theory of defect production in solids by neutrons and displaced atoms.[3]

* Supported in part by the U. S. Atomic Energy Commission.
[1] H. G. Dehmelt, Am. J. Phys. 22, 110 (1954).
[2] G. E. Pake, Am. J. Phys. 18, 438 and 473 (1950).
[3] J. A. Brinkman, Am. J. Phys. 24, 256 (1956).

6. Effect of Impurities in the Vapor Phase on Tarnishing Reactions.* Kurt Lehovec and Donald M. Smyth, *Sprague Electric Company.*—Deviations from the classical parabolic law for tarnishing[1] of silver in halogens have been observed using iodine and bromine atmospheres containing traces of water vapor or carbon tetrachloride vapor. In these cases the tarnished film initially grows in proportion to the tarnishing time, indicating a surface "reaction" at the tarnish film-gas interface as being the rate-determining step for the tarnishing process. A tentative theoretical explanation will be offered based on the assumption that the adsorption of impurity vapor at the silver halide surface causes a surface charge which induces a space-charge layer in the silver halide adjacent to its surface. The flow of silver ions and "holes" (missing electrons) through this space-charge layer may then be the rate-determining step rather than the diffusion of holes through the bulk of the silver halide, as assumed by Wagner's[1] classical theory.

* Work sponsored by the Signal Corps Engineering Laboratories, Fort Monmouth, New Jersey.
[1] C. Wagner, Z. physik. Chem. 21B, 25 (1933); 32B, 447 (1936).

The American Physical Society

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Please cut along this line

(To be sent to Professor E. A. Long, University of Chicago, 5640 South Ellis Avenue, Chicago 37, Ill.)

I EXPECT to attend the dinner of the American Physical Society at 6:30 on Friday evening, March 28. My party will comprise ..... persons.

(*Name*).....

(*Address*).....

(If you want your tickets held to the time of the banquet itself, send a check for **$4.00** per plate, made out to American Physical Society. If you want them mailed to you, send a stamped self-addressed envelope.)